ANL/EES-TM-224

Energy and Environmental Systems Division
Systems Engineering and Technology Group

Program Summary

ARGONNE NATIONAL LABORATORY

Operated by
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This informal report presents preliminary results of ongoing work or work that is more limited in scope and depth than that described in formal reports issued by the Energy and Environmental Systems Division.

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May 1983

work sponsored by

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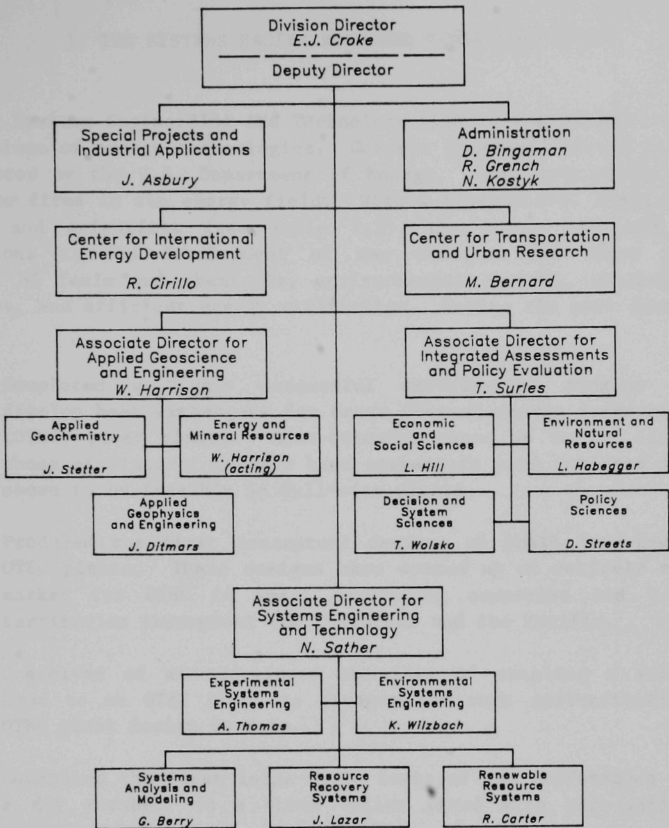
CONTENTS

FOREWORD

This report describes the research and development programs conducted by the Systems Engineering and Technology Group, one of six major professional staff groups within the Energy and Environmental Systems Division of Argonne National Laboratory (see organization chart on facing page).

Through applied research and development programs and policy analysis, the Energy and Environmental Systems Division produces information on the performance and economics of advanced energy systems and the costs and benefits of public-sector initiatives. The Division specializes in systems-oriented planning, policy evaluation, technology development, and assessment studies; its analytical and experimental research programs are carried out in cooperation with the academic community, industry, and other Argonne divisions.

Argonne National Laboratory, one of the nation's leading energy research centers, develops and assesses nuclear and alternative energy systems and conducts a broad range of programs in the physical, environmental, and biomedical sciences. Operated by the University of Chicago under contract to the U.S. Department of Energy, Argonne has a fiscal 1983 operating budget of about $229 million. Laboratory programs are funded primarily by the Department of Energy, with additional support from other federal agencies, state agencies, and the private sector.



Energy and Environmental Systems Division: Organization Structure

1 THE SYSTEMS ENGINEERING AND TECHNOLOGY GROUP

The Systems Engineering and Technology (SET) Group conducts engineering investigations of energy technologies. Current programs, listed in Table 1.1, are sponsored by the U.S. Department of Energy, other governmental agencies, and private firms in the energy field. With a professional staff of about 35 engineers and scientists (see Table 1.2), the Group has made important contributions to the development of new concepts for power generation, production of fuels and chemicals, environmental control, resource recovery from wastes, and efficient energy utilization. During the past four years the Group has:

- Completed a highly successful experimental program to develop heat exchangers for ocean thermal energy conversion (OTEC) power plants. Heat-transfer rates up to 2.5 times those of state-of-the-art heat exchangers were achieved and shown to be feasible in full-size plants.

- Produced the first conceptual designs of small land-based OTEC plants. These designs have opened up an entirely new market for OTEC in small developing countries and U.S. territories throughout the Caribbean and the Pacific.

- Conceived of and developed the idea of coupling a solar pond to an OTEC plant to produce the most cost-effective OTEC plant design to date.

- Conducted the first large-scale tests of the performance of a dry scrubber in a steam boiler fired with high-sulfur coal.

- Shown by means of an engineering analysis that superconducting magnets can be used effectively to remove the sulfur-containing mineral components of high-sulfur coal.

- Shown from tests conducted on pilot plants that there is a close link between the toxicity of condensate water produced in biomass and coal gasification and the toxicity of diesel exhausts and other emissions from the combustion or pyrolysis of hydrocarbons.

- Shown in laboratory tests that strains of the fungus *Fusarium* can perform all the steps in converting wood and other cellulosic feedstocks to ethanol at higher efficiencies than have been obtained with any other microorganism.

Table 1.1 Current Programs, Systems Engineering and Technology Group[a]

Sponsor, Program	FY 1983 Budget ($1000)	Year Initiated
DOE, Ass't Sec'y for Conservation and Renewable Energy		
Energy from Municipal Waste	2480	1977
OTEC Biofouling and Materials Studies	888	1976
OTEC Power Systems Development	610	1976
Resource Recovery from Industrial Wastewater	600	1981
Cogeneration Systems	617	1978
Biomass Environmental Research	140	1979
Heat Exchangers for Low-Grade Heat	85	1983
Geothermal Wastewater Treatment	50	1983
Alcohol Fuels Environmental Research	42	1980
DOE, Ass't Sec'y for Fossil Energy		
SO_x/NO_x Flue Gas Cleaning Systems	400	1981
Coal Gasification Environmental Research	719	1978
Great Plains Coal Gasification Project Support	168	1982
Coal-Water Slurry Modeling	50	1983
Systems Analysis of Coal Conversion Processes	26	1981
DOE, Office of Energy Research		
High-Energy Physics Test Facilities	40	1983
DOE, Ass't Sec'y for Nuclear Energy		
Nuclear Power Plant Analysis	50	1983
DOE, Solar Energy Research Institute		
Ethanol Production by Fusarium	71	1980
U.S. Environmental Protection Agency		
Dry Scrubber Performance Tests	267	1982
Impacts of Coal Cleaning	36	1982
Federal Emergency Management Agency		
Methods for Upgrading Fallout Shelters	160	1982
ANL, Program Development Funds		
Magnetic Coal Cleaning	60	1983
Alfa Laval Inc.		
Heat Exchanger Performance Tests	50	1983
Gas Research Institute		
Environmental Effects of Pipeline Installation	369	1982

[a]As of May 1, 1983.

Table 1.2 Current Staff, Systems Engineering and Technology Group (N.F. Sather, director)

Section	Staff Members: Name	Staff Members: Discipline
Environmental Systems Engineering	K. Wilzbach, manager	Chemist
	D. Livengood, deputy	Environmental systems engineer
	J. Anderson	Computer scientist
	M. Clinch	Mechanical engineer
	R. Doctor	Chemical engineer
	P. Farber	Chemical engineer
	J. Harkness	Chemical engineer
	H. Huang[a]	Chemical engineer
	W. Klausmeier	Environmental scientist
	E. Lynch	Chemical engineer
	C. Swietlik	Scientific assistant
Experimental Systems Engineering	A. Thomas, manager	Mechanical engineer
	F. Davis	Mechanical engineer
	L. Genens	Mechanical engineer
	D. Hillis	Mechanical engineer
	C. Panchal	Chemical engineer
	H. Stevens	Mechanical engineer
Resource Recovery Systems	J. Lazar, manager	Mechanical engineer
	A. Antonopoulos	Biochemical engineer
	J. Bogner	Environmental engineer
	C. Brooks	Management information analyst
	H. Bushby	Mechanical engineer
	J. Faddis	Mechanical engineer
	M. Jain	Mechanical engineer
	O. Ohlsson[b]	Mechanical engineer
	V. Pearson	Mechanical engineer
	C. Shepard	Management information analyst
	F. Stodolsky	Mechanical engineer
	E. Wene	Biochemical engineer
Renewable Resource Systems	R. Carter, manager	Civil engineer
	B. Broomfield	Environmental scientist
	F. Kremer	Environmental systems engineer
	M. Torpy	Environmental systems engineer
Systems Analysis and Modeling	G. Berry, manager	Mechanical engineer
	L. Chow[b]	Mechanical engineer
	C. Dennis[b]	Mechanical engineer
	C. Lee	Mechanical engineer
	R. Lyczkowski[c]	Mechanical engineer
	N. Reddy	Chemical engineer

[a]On full-time assignment from ANL Chemical Technology Division.

[b]On full-time assignment from ANL Engineering Division.

[c]On full-time assignment from ANL Components Technology Division.

- Conducted the first comprehensive experimental investigation of high-efficiency pulse-combustion gas furnaces and developed the first performance analysis and design procedure for these appliances.

- Developed the first procedure for optimizing the design of compressed-air energy storage plants.

Two important characteristics of the SET Group and its work are apparent from the nature of these accomplishments. First, the dominant feature of SET work is an emphasis on the systems approach in carrying out engineering investigations. In contrast to the work of other engineering groups at the Laboratory, which specialize in more narrowly focused research and component development work, our preoccupation is with the operation and performance of entire processes or systems. Our purpose is to develop integrated power systems and energy conversion processes that are optimized with respect to cost-effectiveness, use of energy resources, and control of waste products and pollutant emissions.

A second characteristic of the SET Group is its extensive collaboration with other groups and individuals as a means of increasing the range and strength of its capabilities. Strong ties have been developed with the various assessment and policy evaluation groups in EES and with R&D groups in other ANL divisions, especially those in Chemical Technology, Materials Science and Technology, Biology and Medicine, Chemistry, Components Technology, and High Energy Physics. No less essential to the work of the Group are the partnerships established with engineering staffs from a number of private firms and with faculty from over 20 universities (see Tables 1.3 and 1.4).

Sections 2-7 of this report briefly describe our current programs. These summaries cover the purposes, methods, and principal findings of each program; they are intended to provide a quick overview of the interests, capabilities, and accomplishments of the Group. Recent SET publications are listed in Sec. 8.

Table 1.3 SET Group Interaction with Industry, 1982

Company	R&D Collaboration	Project Review
Alfa Laval	x	
American Iron & Steel Institute	x	x
American Metal Finishers Assn.	x	
Amoco R&D Center	x	
Battelle Columbus Laboratories	x	
Biphase Energy Systems		x
Cal Recovery Systems, Inc.	x	
Citibank		x
Consolidation Coal Co.	x	
Culp, Wesner, Culp	x	
Dart and Kraft Co.		x
Dynatech R&D Co.		x
EG&G Inc.	x	
Environmental Research & Technology	x	x
Fauske and Associates Inc.	x	x
Gas Research Institute		x
General Electric	x	
Hagler Bailly		x
Institute of Gas Technology	x	x
International Nickel Co.	x	
JeCON Engineers		x
Joy Manufacturing, Inc.	x	
Kelley Co.	x	
Lockheed Missiles and Space Co., Inc.	x	
Mandeville & Associates		x
Natural Energy Laboratory of Hawaii	x	
Niro Atomizer, Inc.	x	
Northern Energy Corp.	x	
Pacific Gas & Electric	x	x
Peat, Marwick & Mitchell	x	
Portland Cement Assn.	x	
Rasor Associates		x
Roy F. Weston Co.		x
SETS, Inc.	x	
SPM Group, Inc.	x	
Standard Oil of Indiana	x	x
Systems Technology	x	x
TRW	x	x
Teledyne International	x	
The Hodges Co.	x	
Thermal Resource Corp.	x	
Thermo Electron Corp.		x
Trane, Inc.	x	
Union Carbide, Linde Division	x	
Union Oil Products		x
Westinghouse Electric Corp.		x

Table 1.4 SET Group Interaction with Universities, 1982

University	R&D Collab-oration	Peer Review
Arizona State U.	x	
Carnegie-Mellon Institute	x	
Cornell U.		x
Drexel U.	x	x
Georgia Institute of Technology	x	
Hofstra U.		x
Illinois Institute of Technology		x
Illinois State U.[a]		
Manhattan College	x	
North Texas State U.	x	x
Northwestern U.[a]		x
Ohio State U.	x	
Oklahoma State U.		x
Purdue U.	x	
Texas A&M U.	x	x
U. of California	x	
U. of Hawaii	x	
U. of Illinois[a]	x	x
U. of Massachusetts	x	x
U. of Pennsylvania		x
U. of Wisconsin		x
Washington State U.		x

[a] Also student employee from this university.

2 OCEAN THERMAL ENERGY CONVERSION

Ocean thermal energy conversion (OTEC) is the subject of a major SET effort involving systems analysis, laboratory experiments, and field tests. In OTEC power systems, solar energy stored in the form of warm ocean water is converted into electricity. The warm water is used to evaporate a working fluid (such as ammonia) in a heat exchanger. The vapor formed in the evaporator is sent through a Rankine-cycle engine consisting of a turbine and a second heat exchanger, which condenses the vapor, using cold deep ocean water as the coolant. A pump returns the liquid working fluid to the evaporator to begin the cycle again. The thermal energy extracted by the turbine is transformed into electrical energy by coupling the turbine to a generator.

Our OTEC research began in 1976 in response to DOE's need for a facility in which to test the performance of the low-temperature-difference heat exchangers used in OTEC systems. We constructed a test facility and operated it successfully and were later given responsibility for studies of heat exchanger biofouling and corrosion.

Heat exchanger performance tests and biofouling and corrosion studies -- described in Secs. 2.2 and 2.3, respectively -- have been the major focus of laboratory and field studies. Other efforts, discussed in Sec. 2.1, have dealt with total system design and concept evaluation. Our small-plant studies have identified several design issues crucial to the success of OTEC pilot plants.

Engineering evaluations of OTEC plants made before the mid-1970s were generally inconclusive due to a lack of experimental data on system and component performance. EES programs, planned with assistance from university and industry experts, have produced a considerable body of published data to fill this gap. Through participation in the review of numerous OTEC plant design studies made by various organizations, we have transferred the knowledge gained in our OTEC research directly to industrial plant designers.

2.1 ENGINEERING DESIGN OF OTEC POWER PLANTS

Scope and Approach

Designs for complete OTEC power systems have been developed or evaluated and engineering cost estimates have been made for several types of plants, including:

- Pilot plants;
- Small (10 MWe or less) shore-based OTEC power plants, which are of special interest to oil-dependent island nations;
- Small OTEC plants in which a salt-gradient solar pond replaces the warm surface waters of the ocean as a heat source; and
- A closed-cycle test facility using surplus equipment from the OTEC-1 ocean-based demonstration facility.

Results

EES has assisted DOE in evaluating pilot plant designs being prepared by two DOE contractors: General Electric and Ocean Thermal Corporation. The conceptual designs are nearly complete, and preliminary engineering design is about to begin. Both designs are for 40-MWe, tower-mounted plants located slightly off the shore of the Hawaiian island of Oahu.

We have reviewed all contractor design reports, developed guidance on optimum designs, and provided engineering results from OTEC R&D programs at ANL and elsewhere for incorporation into the designs. In particular, our heat exchanger test programs (see Sec. 2.2) produced thermal hydraulic test data on a new heat exchanger concept used by one of the contractors. Biofouling control data generated by EES at the OTEC Seacoast Test Facility in Hawaii enabled the designers to reduce their heat exchanger surface requirements by 8%, reducing plant cost by about $100/kWe.

Our design studies of small OTEC plants show that there are appreciable economies of scale for the seawater systems and the plant structures, but rather limited economies of scale for the power system components, including the heat exchangers. The overall plant cost as a function of generating capacity is plotted in Figure 2.1. For the 10-MW plant, the estimated cost of electrical power is 170 mills/kWh. Although this rate is not competitive with those of large generating units on the U.S. mainland, such small plants may be very attractive to oil-dependent island countries.

The combination of an OTEC plant with a solar pond was an Argonne innovation based on OTEC work by EES and solar pond research by the Components Technology Division. The configuration is illustrated in Figure 2.2. The design study showed that, compared to a conventional OTEC plant, the solar pond design is five times more efficient thermally, and therefore requires five times less capacity in the cold-water system. The offsetting cost is for the solar pond, which becomes the major cost item and which has its own set of design and construction problems. On balance, however, it appears that the solar-pond/OTEC hybrid has fewer operational uncertainties and can be built for about two-thirds the cost of a comparable conventional OTEC plant.

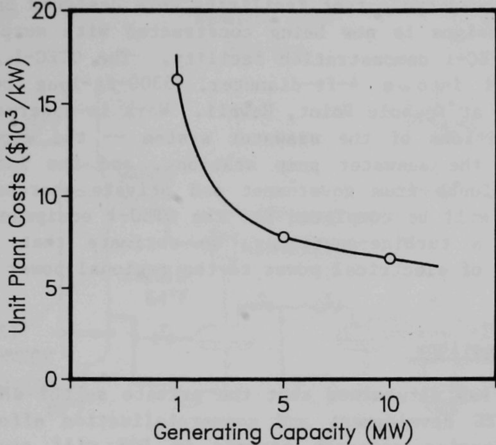


Fig. 2.1 Unit Plant Cost versus Generating Capacity for Small OTEC Plants

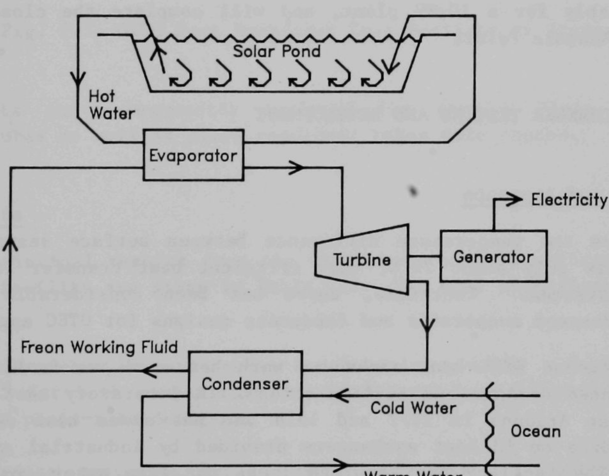


Fig. 2.2 Schematic of Combined Solar-Pond/OTEC System

Several closed-cycle test facilities were designed and a facility based on one of the designs is now being constructed with surplus equipment from DOE's seagoing OTEC-1 demonstration facility. The OTEC-1 cold water pipe is being reassembled into a 4-ft-diameter, 5300-ft-long pipe that will be deployed offshore at Keahole Point, Hawaii. Work is underway on the design of the remaining portions of the seawater system -- the warm-water and mixed-discharge pipes, the seawater pump stations, and the intake and discharge structures. If funds from government and private sources can be obtained, these structures will be completed and the OTEC-1 equipment installed. With the purchase of a turbine-generator, we estimate that the facility will contribute 700 kW of electrical power to the regional power grid.

Future Directions

While DOE has determined that the private sector should now undertake the remaining OTEC development and commercialization efforts, it is likely that a modest ongoing research program in DOE will continue for several years. This program will emphasize advanced OTEC concepts, including open-cycle systems and thermoelectric OTEC, and new integrated fresh-water/power-generation concepts. We anticipate that Argonne, as lead laboratory for OTEC power systems development, will continue to support the pilot plant design effort, probably for a 10-MW plant, and will complete the closed-cycle test facility at Keahole Point.

2.2 HEAT EXCHANGER TESTING AND DEVELOPMENT

Scope and Approach

Because the temperature difference between surface seawater and deep ocean water is only about 20°C, very efficient heat transfer is required in OTEC power systems. Therefore, there has been considerable interest in developing advanced evaporator and condenser designs for OTEC applications.

The Argonne OTEC heat exchanger work has used two facilities to test various advanced designs and configurations. A laboratory test facility was constructed at Argonne in 1977 and 1978 and has since been used to obtain performance data on 13 heat exchangers provided by industrial and university designers. The facility has separate loops for warm water, cold water, and the working fluid (ammonia or freon) and is designed for heat exchangers for 25-kW OTEC plants (see Figure 2.3).

The other facility was sea-based and was designed to test only a small number of heat exchangers for 1-MW plants under actual ocean conditions. Called OTEC-1, this facility was built by DOE and operated off the coast of Hawaii during late 1980 and early 1981. Argonne planned the OTEC-1 tests with input from industry and university consultants, and our engineers participated

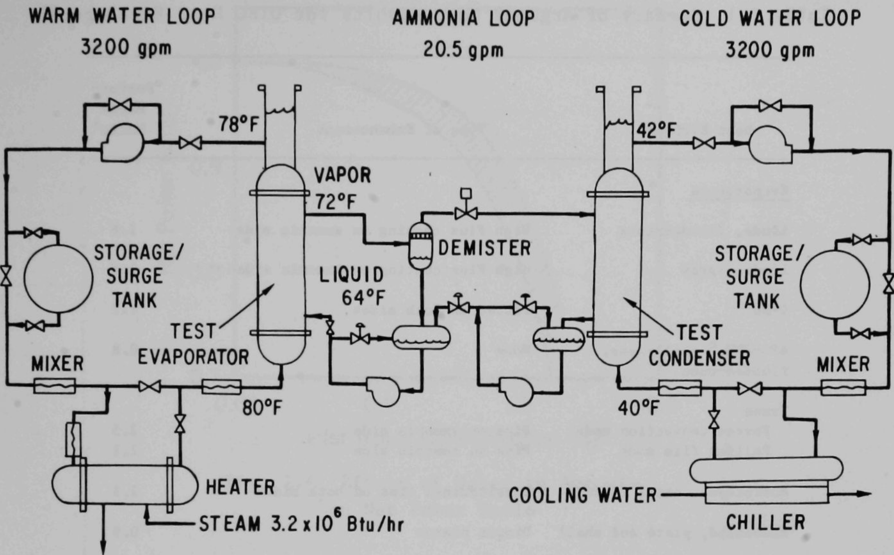


Fig. 2.3 OTEC Heat Exchanger Test Facility at Argonne

in the tests and subsequently analyzed the data. Plain and enhanced evaporator tubes as well as plain condenser tubes were tested.

Results

The principal results from the five years of heat exchanger testing on the Argonne facility are given in Table 2.1. The most significant conclusions are:

- Heat-exchanger performance has been improved by a factor of 2.5 for both evaporators and condensers over state-of-the-art plain-tube designs.

- Because contamination of ammonia by water in excess of about 0.1% results in a appreciable degradation of performance (see Figure 2.4), ammonia purification systems must be included in OTEC plant designs.

- The performance of plate-frame evaporators designed originally for liquid-to-liquid service can be improved by a factor of 2 by the addition of nucleation enhancement to the ammonia side, to aid boiling heat transfer.

Table 2.1 Summary of Argonne Test Results for OTEC Heat Exchangers

Heat Exchanger	Type of Enhancement	Performance Ratio[a]
Evaporators		
Linde, flooded-tube	High Flux coating on ammonia side	1.6
Linde, spray	High Flux coating on ammonia side	1.5
C-MU[b]	Fluted on both sides	1.7
APL-JHU,[c] shell-less, flooded-tube	None	0.8
Trane		
Forced convection mode	Fins on ammonia side	2.5
Falling film mode	Fins on ammonia side	2.1
Rocketdyne, axial fluted	Longitudinal fins on both sides	2.3
Rosenblad, plate and shell	Dimple plates	0.9
Tranter, plate (#1)	Chevron plates	1.2
Tranter, plate (#2)	Linde High Flux coating on ammonia side; Chevron plates on water side	2.4
Trane, extruded channels	Fins on ammonia side	2.4
Alfa-Laval, plate	Chevron plates	1.2
Condensers		
Linde	Wire wrap on ammonia side; fins on water side	1.6
C-MU	Fluted on both sides	2.1
C-MU evaporator tested as a condenser	Fluted on both sides	2.5
APL/JHU evaporator tested as a condenser	None	1.0
Trane evaporator tested as a condenser	Fins on ammonia side	1.7
Trane extruded-channel evaporator tested as a condenser	Fins on ammonia side	2.0

[a]Performance ratio = (overall heat transfer coefficient for baseline operating condition) ÷ (overall heat transfer coefficient for a conventional, smooth-surface shell-and-tube heat exchanger).

[b]C-MU = Carnegie-Mellon University.

[c]APL-JHU = Applied Physics Laboratory, Johns Hopkins Unive

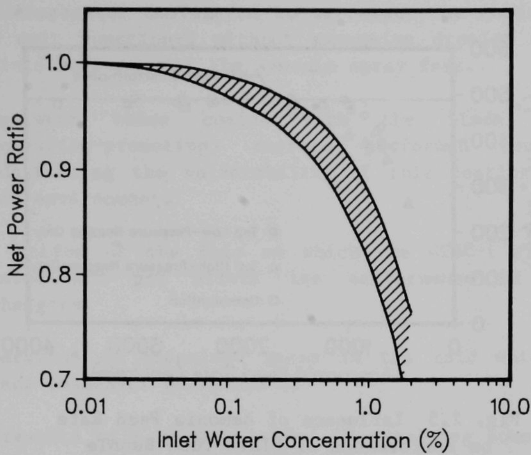


Fig. 2.4 Effect of Water in Ammonia on Net Power Ratio

- Brazed aluminum plate-fin exchangers offer a powerful combination of high performance and low initial cost. This has encouraged vendors and others to seek ways to make aluminum exchangers suitable for seawater service and to adapt this design to other materials.

A good indication of the contribution that the Argonne heat-exchanger test program has made can be seen in the trend of cost estimates for OTEC power plants. When the test program was started, it was generally believed that heat exchangers contributed more than half the cost of an OTEC plant. Today, at least partly because of the ANL development work, the heat exchangers are now expected to account for less than one-third of the total plant cost.

The OTEC-1 sea-based test program, although cut from the original nine-month period to three months, produced a number of significant results on heat exchanger performance under open sea conditions.

As can be seen from Figure 2.5, the plain-tube bundle evaporator performed at sea as predicted from static considerations. However, the enhanced-tube bundle evaporator did not perform as predicted by laboratory tests, apparently because of fouling of the High Flux surface (see Figure 2.6). Performance of the condenser tested was in agreement with predictions based on single-component (water) flow in the tubes. Based on analysis of the OTEC-1 test data, the following conclusions can be reached:

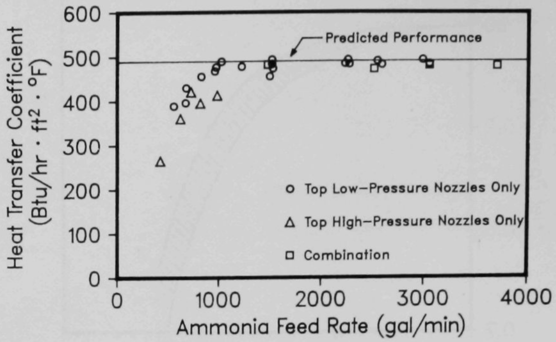


Fig. 2.5 Influence of Ammonia Feed Rate on Performance of Plain-Tube Bundle Evaporator Aboard OTEC-1

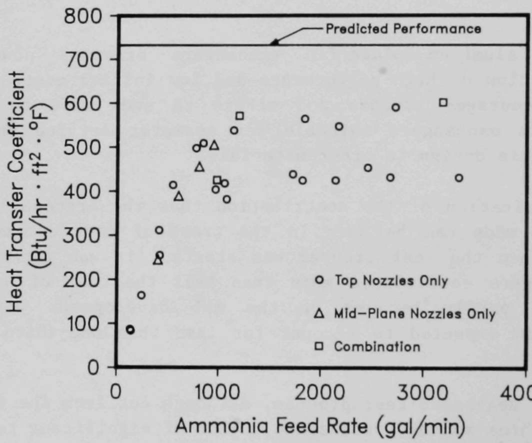


Fig. 2.6 Influence of Ammonia Feed Rate on Performance of Enhanced-Tube Bundle Evaporator Aboard OTEC-1

- The evaporator configured to represent one quadrant of a 4 MWe unit functioned without excessive droplet entrainment or interference with the ammonia spray feed.

- Evaporator tubes coated with the Linde High Flux (nucleation-promoting) surface performed poorly, thus demonstrating the vulnerability of this coating in a open ocean environment.

- The motion of the ship on which the OTEC-1 facility was mounted did not affect the performance of the heat exchangers.

- Liberation of dissolved gases in the cold water did not affect condenser performance.

These results will be very useful in resolving some of the engineering difficulties encountered in actual OTEC plant operation at sea.

Future Directions

Funding for the Argonne heat exchanger test facility for OTEC research program is not expected beyond the current fiscal year. However, the DOE Office of Industrial Programs and some private companies have expressed interest in continued operation of the facility on a reduced scale.

Funding is now being provided by the DOE industrial cogeneration program for the procurement and testing of a spirally fluted tube condenser to be constructed by the General Atomic Company. We are currently negotiating with Alfa-Laval, Inc., to test, on a cost-sharing basis, its plate heat exchanger as a condenser for both ammonia and freon (this exchanger has been tested as an evaporator with DOE funds).

2.3 BIOFOULING AND MATERIALS TESTS

Scope and Approach

As seawater flows through an OTEC heat exchanger, the heat transfer surfaces are fouled by the gradual deposition and growth of colonies of microorganisms. If this biofouling is not controlled, heat-exchanger performance is impaired, and eventually the plant has to be shut down. Furthermore, seawater corrodes many materials used in heat exchangers, pumps, and other plant components.

Over the last three years, Argonne has conducted biofouling and corrosion experiments at the nearshore Wrightsville Beach test facility; the

Punta Tuna, Puerto Rico, open-ocean test facility, and the Hawaiian seacoast test facility. Table 2.2 summarizes the biofouling test programs.

We supervised the design, construction, and operation of the Hawaiian test facility. As part of the research effort, Carnegie-Mellon University developed a heat-transfer monitor for circular channels, which was later modified by Argonne. It was further modified for noncircular channels, including those with enhanced heat-transfer promoters on the surfaces. The heat-transfer monitor is used for accurate, on-line measurements of the biofouling buildup on heat exchangers. The rate of corrosion of heat exchanger materials is measured using sample coupons that are installed in the flow system.

Results

Biofouling of Titanium Surfaces. The rate of biofouling is low for the first manual cleaning cycle, while that for the subsequent cleaning cycles is higher and nearly the same, as shown in Figure 2.7. The rate of biofouling also was found to be comparable for the titanium and aluminum surfaces and negligible for deep, cold seawater. The rate of biofouling on the open sea (Punta Tuna) is about 50% less than that near shore (Wrightsville Beach).

All of the countermeasures evaluated, except the technique using a chemical surfactant, could control the biofouling buildup for several months if used often enough. Intermittent chlorination (0.05 ppm for 1 hr/day) can

Table 2.2 Biofouling Tests

Location	Materials Tested	Antibiofouling Measures Tested
Wrightsville Beach	Titanium Aluminum alloy	Manual brushing Chlorination Sponge ball cleaning Abrasive slurry Surfactant/disperant
Punta Tuna	Titanium Aluminum alloy	Manual brushing Chlorination
Hawaii	Titanium Aluminum alloy Stainless steel	Manual brushing

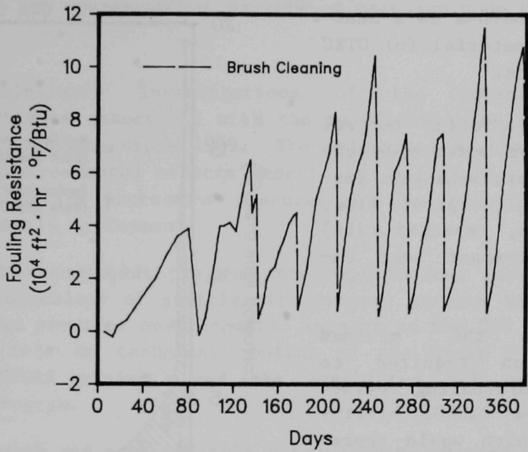


Fig. 2.7 Fouling Resistance versus Time, in Punta Tuna Experiments

keep titanium heat-exchanger surfaces sufficiently clean for at least one year. In addition, chlorination can be used to clean already-fouled surfaces.

Corrosion and Biofouling of Aluminum Alloy Surfaces. Three basic types of aluminum alloy were tested: a 3004 alloy, with and without a cladding containing zinc; a zinc-coated 3003 alloy, and a 3003 Alclad alloy. For the nearshore seawater, intermittent chlorination is less effective for preventing biofouling on 3003 Alclad than on titanium. However, for open seawater, intermittent chlorination can effectively keep the heat-exchanger surface clean.

The rate of corrosion is quite sensitive to the frequency and intensity of mechanical cleaning (such as manual brushing and Amertap ball cleaning). While the initial rate of corrosion for the aluminum surface is high (see Figure 2.8), the assymptotic value is low. If these test data are supplemented by long term (>2 years) corrosion data, aluminum could be qualified for the OTEC heat exchangers. The corrosion rate for zinc-coated surfaces was found to be comparable to that for Alclad surfaces.

Future Directions

We plan to continue the biofouling and materials research program for several more years at the Seacoast Test Facility. The major objectives will be to:

- Qualify aluminum as a heat-exchanger material for OTEC applications.

- Develop biofouling control methods for water-side enhanced heat-exchanger surfaces (e.g., spiral fins, axial fins, repeated ribs) and for compact heat exchangers.

- Determine the minimum chlorination required to keep the biofouling resistance below 0.0001 hr-ft^2-°F/Btu, which would represent a heat-transfer degradation of about 10% in a high-performance heat exchanger.

- Evaluate alternatives to chlorination as a biofouling control method.

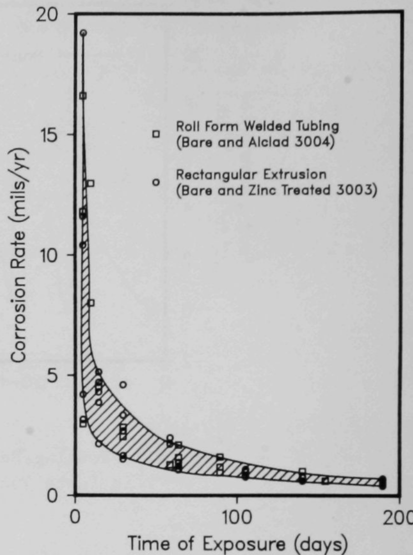


Fig. 2.8 Corrosion Rates for Candidate Aluminum Surfaces

3 HEALTH AND ENVIRONMENTAL EFFECTS OF COAL AND WOOD GASIFICATION

Multidisciplinary investigations of the potential health and environmental effects associated with the gasification of coal and wood have been underway at Argonne since 1979. The objectives of these programs are to determine the environmental effects generic to gasification technology and to identify the necessary protective measures and environmental control systems prior to large-scale deployment.

Six of the component programs are experimental investigations of the chemistry and toxicology of gasification process streams and effluents. The remaining program provides environmental support to the DOE Chicago Operations Office in its role as technical monitor of the Great Plains Gasification Project (the HYGAS project) and the associated $12 million health and environmental program.

The approach and scope of this research have changed significantly with time. When the programs were initiated, the development, demonstration, and commercialization of advanced coal gasification processes represented a major DOE initiative. A parallel program of process- and site-specific health and environmental research was to be conducted, at levels commensurate with the stage of process development. Because the most advanced gasification processes were still at the pilot-plant stage, and because many of the experimental techniques for environmental analysis of coal-derived materials were not well developed, this philosophy effectively restricted early efforts to the chemical and toxicological screening of process materials and to the development of methodologies needed for more-comprehensive analyses.

Our initial studies at the HYGAS pilot plant, carried out in collaboration with the Institute of Gas Technology, were of this variety. In that work we demonstrated that a simple toxicity assay, such as the Ames *Salmonella* test for mutagenicity, could be used to provide unique process information. This development, together with the shift in emphasis at DOE to generic, long-range research, gradually allowed us to broaden the scope of the program in subsequent studies covering process samples from the Grand Forks Energy Technology Center (GFETC) gasifiers, a coal pyrolysis research unit at Mellon Institute, and an advanced wood gasifier developed by Battelle Columbus Laboratories.

Emphasis in the more recent studies has been on three areas:

- Characterization of acute and chronic toxicity in laboratory animals resulting from exposure to the oil and tar by-products of gasification,

- Isolation and identification of the specific chemicals responsible for the mutagenicity of gasification by-products, and

- Determination of cause-and-effect relationships between process conditions and by-product chemistry and toxicology.

An important factor in the success of these research programs is the high degree of interaction between EES staff and staff from other ANL divisions and between Argonne staff and personnel in related programs at universities and other national laboratories. In particular, staff from Argonne's Biological and Medical Research Division play an integral role in this program.

3.1 TOXICITY OF PROCESS STREAMS AND EFFLUENTS

Scope and Approach

The initial studies of the environmental effects of gasification focused on the HYGAS plant and the GFETC gasifiers. To determine the magnitude of potential health effects and to identify needed research, samples of oil and tar were evaluated for toxicity, using a comprehensive, tiered screening procedure. Materials from four types of coal gasifiers and one wood gasifier were studied.

Short-term cellular assays were employed to measure genotoxicity and cytotoxicity. Materials found to be active in the cellular screen, or that possessed a high probability for significant human exposure, were then evaluated in whole animals. Mammalian toxicology procedures were used to evaluate acute effects in mice and rabbits and chronic effects in guinea pigs and mice.

Results

Our research has shown that gasification by-product materials are mutagenic (following metabolic activation) in the Ames *Salmonella* assay. They also induce sister chromatid exchanges and inhibit cell growth in mammalian cells (mouse myeloma cells). Similarly, rabbit alveolar macrophages exposed to such materials *in vitro* show decreased functional ability (phagocytosis).

The effects of two of the by-products (HYGAS recycle oil and GFETC tar) on whole animals also were studied. The results are shown in Table 3.1. The HYGAS material induced substantial to severe ocular damage and irritation (persistent corneal damage and conjunctivitis) and was a substantial skin irritant following an acute exposure in albino rabbits. A moderate ocular response (minor, immediate inflammation that cleared within 24 hours) and only mild skin irritation were noted following exposure to GFETC tar. In addition, HYGAS recycle oil contained components that induced strong allergenic reactions in guinea pig skin.

Table 3.1 Results of Whole Animal Studies Carried Out with Selected Tars

Type of Effect	Result
Acute effects	
LD_{50} (lethal dose to 50% of animals tested)[a]	Positive
Dermal toxicity	Positive
Eye irritation	Positive and negative
Chronic effects	
Delayed hypersensitivity	Positive and negative
Carcinogenicity	Highly positive

[a]Oral and intraperitoneal doses.

Mice were dermally exposed by repeated skin painting, and both by-product materials were found to be strong carcinogens, inducing squamous cell carcinomas. Biochemical measurements indicated some systemic damage, but no overt histopathological damage.

The carcinogenicity of fractionated GFETC tar (acid, base, and neutral fractions) that was skin-painted at concentrations equivalent to that of the whole tar has also been determined and is shown in Figure 3.1. As seen in the figure, the neutral fraction is significantly more carcinogenic than the whole tar. Although the specific mutagenicity of the basic tar fraction is more than 30 times that of the neutral tar fraction, the lower concentration of basic materials results in a tumorogenic activity significantly less than that of the neutral fraction. Finally, the data show that dermal carcinogens are present in the acid fraction, a material that consistently gave negative results in Ames assays.

Future Directions

The results indicate the need for continued evaluation of the toxicity of gasification by-products. The general data base is now sufficient to begin to evaluate low-dose effects (more closely related to potential human exposures), dose-response relationships, and the fate and metabolism of major toxicants.

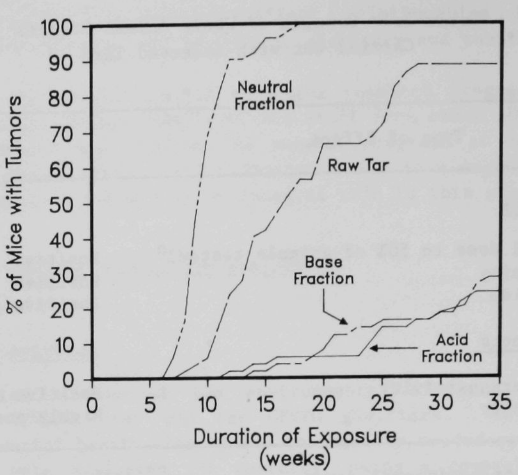


Fig. 3.1 Skin Cancer Resulting from Painting Mice Skin with Tar Fractions and Raw Tar from the GFETC Gasifier

3.2 IDENTIFICATION OF TOXIC AGENTS

Scope and Approach

The initial HYGAS and GFETC work pointed out the need for more-careful screening of the complex compounds making up the gasification by-products. We concluded it was important to identify at least the compound classes, and preferably the specific compounds, responsible for the toxicity, to obtain a basis for planning the more expensive chronic toxicity studies with laboratory animals.

To carry out this screening, EES developed and applied advanced separative procedures and bioassay techniques for identifying toxic agents in coal-derived liquids. This involves the progressive simplification of the mixture by fractionation, using the results of bioassays and chemical analyses on the fractions to select appropriate fractions and fractionation techniques for further studies. Multidimensional fractionation techniques were used, toxicity was screened with the Ames *Salmonella* assay for mutagenicity, and the components of the fractions were identified by gas chromatography/mass spectrometry (GC/MS). This process is commonly referred to as biodirected chemical analysis.

Results

An early result with broad health implications is the finding that, in fractionation by volatility, the mutagenicity of coal-derived liquids is confined to components having higher boiling points (>200°C). In effect, then, separation by volatility is the first step in biodirected chemical analysis and one that greatly simplifies solvent removal in subsequent fractionations.

The next step in the fractionation scheme was to separate the acidic, basic, and neutral components by liquid-liquid partitioning. We have significantly improved the effectiveness of such separations by adding methanol to the aqueous phase to increase the extractability of high-molecular-weight acids and bases from organic solutions. Using this procedure, we have shown that most of the mutagenicity in gasifier tar samples is associated with basic components, which account for only a small fraction of the weight, and that the remaining activity is found in the neutral components, which account for the bulk of the weight (see Figure 3.2).

Efforts to identify the mutagens were focused initially on the basic components because of their higher specific activity. Analysis of the basic fraction by GC/MS showed that it contained two classes of bases, azaarenes and aromatic amines, with the former predominating. We developed a high-performance liquid chromatographic (HPLC) procedure for separating not only the two classes, but also individual bases within the classes. Ames assay of the resulting chromatographic fractions indicated that most of the mutagenicity was associated with the aromatic amines and, in fact, was concentrated in a few fractions. By separating the compounds in these fractions according to molecular size, we were able to conclude that two isomers of

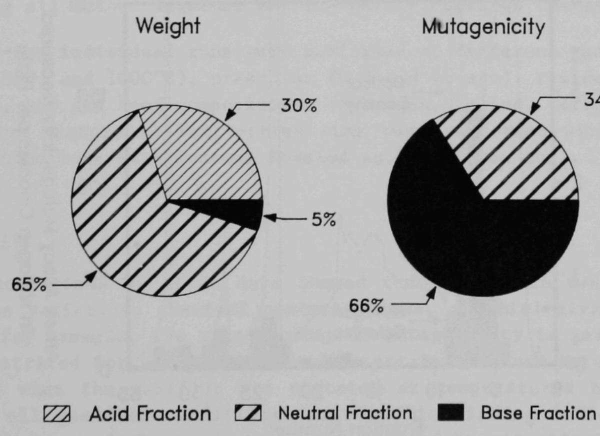


Fig. 3.2 Relative Mutagenicity of Acid, Base, and Neutral Fractions of Gasifier Tar

aminophenanthrene were responsible for virtually all of the mutagenicity. These and other aromatic amines are known to be present in coking tar and to cause bladder cancer.

Mutagens in the neutral tar fraction were initially separated by elution from a silica gel column with solvents of increasing polarity. As shown in Figure 3.3, most of the mutagenicity was associated with three fractions in the nonpolar region. Analysis of these fractions by GC/MS indicated the presence of a range of polycyclic aromatic hydrocarbons (PAHs) containing up to 24 carbon atoms. Subsequent fractionations on HPLC columns, which separate molecules by the number of rings and carbon atoms they contain, allowed us to isolate the specific PAHs responsible for the mutagenicity and identify them by comparison with authentic samples. Surprisingly, in view of the complexity of the tar, the compounds number less than 20, and all are known mutagens and carcinogens. In a recent study of the by-product oil from gasification of wood, we found that the same PAHs were present and at similar concentrations.

The demonstration that the toxic agents in gasification-derived materials are finite in number, and already known, paves the way to implementing meaningful toxicological studies in animals.

Future Directions

Near-term objectives are to isolate and identify the important mutagens in the azaarene and polar neutral classes so that appropriate animal toxicity

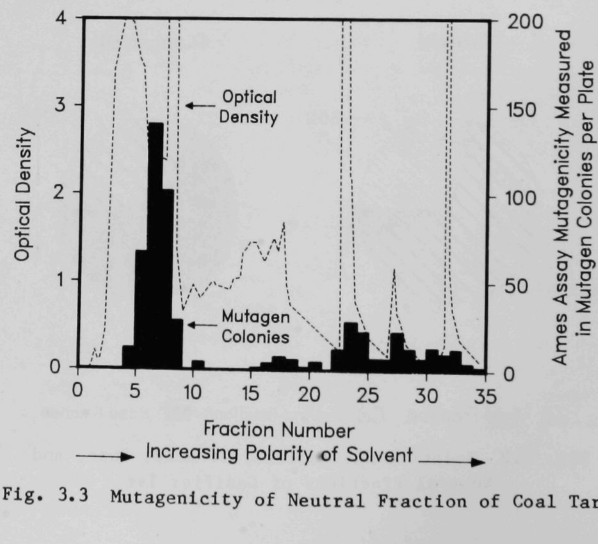


Fig. 3.3 Mutagenicity of Neutral Fraction of Coal Tar

studies can be initiated. We also plan studies of the acid fraction to determine if the failure to observe mutagenicity is attributable to the high toxicity of phenol and cresol components. Another planned activity is the use of other *in vitro* toxicity assays for other effects (such as carcinogenesis or teratogenesis) that are possibly more relevant to human health.

3.3 EFFECTS OF PROCESS CONDITIONS ON COAL DEVOLATILIZATION

Scope and Approach

The gasifier environmental effects program also has addressed process modifications that can reduce the output of toxic by-products. In an experimental study, we conducted a screening-level investigation of the effects of gasification process conditions on the characteristics of gasifier effluents. A bench-scale gasifier was operated to produce effluents under a variety of controlled process conditions. The chemistry and toxicology of these effluents were characterized, and these data were interpreted to find relationships between gasifier process conditions and the yield, chemical, and toxicological data.

The study was a joint effort of ANL, Energy Research and Technology (ERT), Inc., and the Mellon Institute of Research at Carnegie-Mellon University. ERT provided engineering assistance in experimental design, and the Mellon Institute operated the reactor and collected process data and condensate oil and tar samples. Argonne provided chemical and toxicological characterizations of the samples and developed an integrated computerized data base incorporating all data. Together ANL and ERT interpreted the results.

Fifty-two individual runs were performed at different gasifier temperatures (600, 800, and 1000°C), pressures (0.3 and 10 atm), residence times (0.2 and 1.0 sec), and gas feed compositions (hydrogen, helium, carbon dioxide, and a steam/helium mixture). Forty-three runs were performed with North Dakota lignite and nine runs with Montana Rosebud subbituminous coal.

Results

The comparison of these data showed that there are many correlations among process variables, chemical concentrations, and biological effects. In Figure 3.4, for example, the relationship of mutagenicity to gasifier temperature is illustrated for the lignite feed material. Maximum mutagenic activity was obtained when the gasifier was operated at temperatures between 600 and 1000°C, for all gasifier conditions tested; this finding indicates that the production of mutagenic by-products can be reduced by selecting an appropriate gasification temperature.

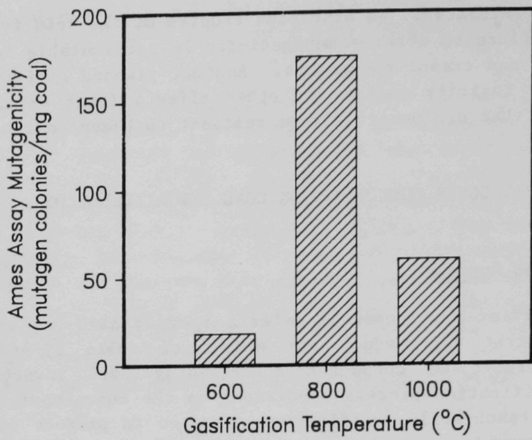


Fig. 3.4 Mutagenicity of Gasifier Tar at Different Gasifier Temperatures

A second relationship between bioactivity and the concentration of a particular class of chemical compounds in the condensate is illustrated in Figure 3.5. The greater the concentration of nitrogen-containing aromatic compounds, such as primary aromatic amines (PAAs) and azaarenes, the greater the bioactivity as measured by the Ames assay. This finding is consistent with other data, since specific PAAs in gasifier tar have recently been shown to cause mutagenicity and may be carcinogenic.

Additional findings are:

- Highest yields of oil and tar occur at low temperature, and at higher temperatures and 0.2 second residence time in the presence of steam.

- The Ames mutagenicity of oils and tars varies widely, from "negligible" to "substantial," over the range of conditions tested; however, oils and tars produced at 600°C are not mutagenic.

- The Ames mutagenicity of oil and tar increases with bulk molecular weight (as evidenced by atomic ratio of carbon to hydrogen).

The conclusions reported here are consistent with the variations seen in the chemistry and toxicology of oils from the HYGAS and GFETC gasifiers (see Secs. 3.1 and 3.2).

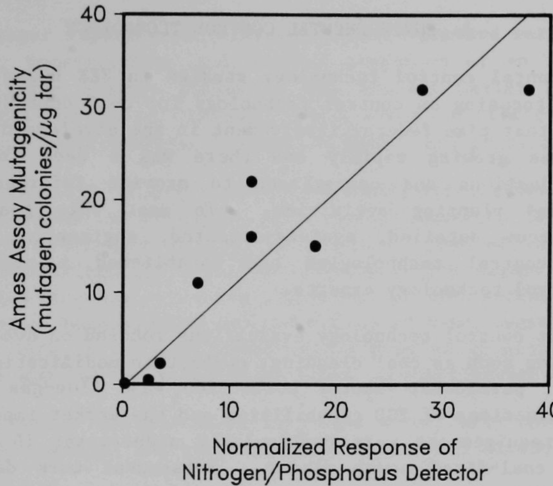


Fig. 3.5 Mutagenicity of Gasifier Tar as a Function of Its Nitrogen Content (tar from Mellon Institute Process Development Unit)

Future Directions

The prospects are excellent that a process modification strategy can contribute significantly to an overall environmental control strategy for the emerging U.S. coal gasification industry. We plan to expand the existing data base to include more process types, operating conditions, coal types, chemical species of significance, and tests for other biological effects.

More extensive interpretation of these data should identify cause-and-effect relationships that will allow the development of a health management model for gasifier operations. This health management model will be used to evaluate the effectiveness of environmental control technologies that are based on process modifications.

4 ENVIRONMENTAL CONTROL TECHNOLOGY

Environmental control technology studies in EES began in 1976 with a single project focusing on control technology for coal combustion by electric utilities. At that time federal involvement in the development of fossil-fuel technologies was growing rapidly and there was a need for comprehensive technology evaluations and comparisons to provide informed input to DOE policymaking and planning activities. To meet this goal, the project developed numerous detailed, systems-oriented, engineering evaluations of environmental control technologies and established a permanent team of recognized control technology experts.

The first control technology evaluations focused on available and near-term technologies such as coal cleaning, combustion modifications for nitrogen oxides control, particulate-matter collection, and flue-gas desulfurization (FGD). Our evaluations of FGD capabilities and the market impacts of proposed coal-cleaning requirements were particularly significant in shaping current standards for coal-fired power plants. Subsequent work dealt with more-advanced technologies, such as preparation and firing of coal-oil mixtures, fluidized-bed combustion (FBC), gasification/combined-cycle power systems, solvent refining of coal, and techniques for removing very fine particulate matter from flue gas. Earlier studies were updated as necessary to keep pace with technology developments and to address specific issues.

In 1979, the project mandate was broadened to include industrial as well as utility coal use. The resulting analyses were unique in their systems approach to evaluating alternative pollution standards for various types of industrial boilers. We were thus able to clearly delineate secondary environmental and resource impacts, as well as point out the importance of economies of scale to fuel and technology choices.

The results of our environmental control technology studies have seen widespread application, as evidenced by the reliance of DOE on program outputs for policymaking; the extensive use by utility and industrial groups of the data and technology simulation models developed by EES; and the continuing, frequent requests for information from government agencies, universities, private industry, and foreign research institutions.

Our present environmental control technology programs reflect an increasing involvement in field studies and laboratory research. One of the first laboratory efforts investigated the effects of high chloride ion concentrations (a problem with Midwestern coals) on the operation of lime-based FGD systems. This work led to the establishment of the Argonne Scrubber Laboratory. This facility is equipped for production of simulated flue gas, on-line analysis of gas-stream compositions, computerized data acquisition and analysis, and small-scale simulation of any flue-gas treatment system of interest. Currently, we are using the facility to study processes for the simultaneous removal of sulfur oxides and nitrogen oxides from flue gas.

On a larger experimental scale, EES staff members were instrumental in the selection, construction, and initial operation of an innovative spray-dryer/fabric-filter cleanup system at the Argonne boiler house. The performance of that system is currently the subject of studies being conducted for both the U.S. Environmental Protection Agency and private industry.

The combination of systems-analysis capability, laboratory facilities, and field experience has generated many opportunities to expand our environmental control technology efforts to include advanced technologies. For example, the possibility of applying superconducting magnet technology -- an existing Argonne strength -- to the removal of pollution-causing impurities in coal has recently been studied and determined to have considerable technical merit. Also, much of the information and expertise developed for coal-based systems can be applied to technologies based on other feedstocks.

The following sections describe projects currently underway in flue gas cleaning, coal cleaning, and environmental control for alcohol production.

4.1 FLUE GAS CLEANING FOR COAL-FIRED BOILERS

4.1.1 Reliability of Flue Gas Desulfurization (FGD) Systems

Scope and Approach

Electric utilities have been concerned that the poor reliability of FGD systems has caused frequent and costly shutdowns of coal-fired power plants. We therefore evaluated performance information on FGD systems operating in electric power plants.

A literature search was performed to determine the frequency of occurrence and types of operating problems encountered in power plant FGD systems. Using the information obtained from the literature search, we performed a computer analysis to relate the reliability of FGD components (subsystems) to the sulfur content of the coal being burned and to the degree of sulfur dioxide removal. This combination of coal sulfur content and sulfur dioxide removal can be expressed as the "stress" placed on the FGD system. A predictive model, encompassing data on 25 major scrubber subsystems, was then constructed and used to relate system stress and specific FGD process type to the reliability of the pollution control system and its components.

Results

A total of 62 commercial flue-gas desulfurization systems representing eight different scrubbing chemistries were surveyed. Figure 4.1 shows both actual and modeled system availabilities for open-water-loop lime and limestone FGD systems. These systems are able to minimize corrosion problems

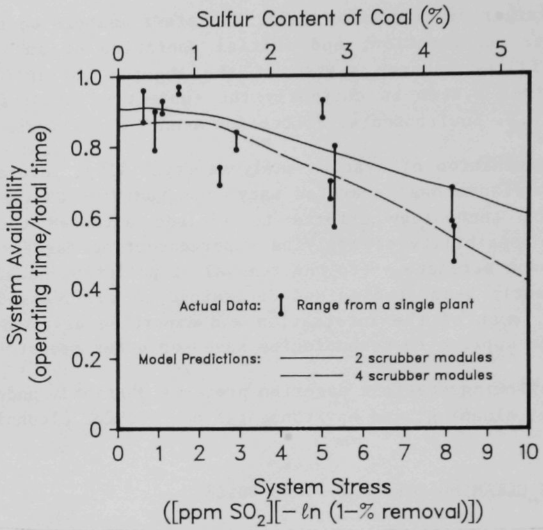


Fig. 4.1 Observed and Modeled Availability for Open-Water-Loop Lime and Limestone FGD Systems

by continually bleeding off some of the scrubber fluid and replacing it with fresh water. This is a significant factor in scrubber operation, since examination of FGD system reliability, both from records and using the EES model, showed a high equipment failure rate for the first 18 months of operation due to corrosion and poor materials design. After this period, our model showed that the subsystems most likely to fail are the fans and ductwork sections. This system model will permit designers to make provisions for the most problematical areas of an FGD system in a cost-effective manner.

Figure 4.2 presents results for five of the major scrubbing chemistries surveyed. The implications are that for combustion of low-sulfur coal (<2.5% S), an open-water-loop, lime-limestone FGD is the most reliable. Utility familiarity with its operation no doubt contributes significantly to this high success rate. When a high-sulfur coal (>2.5 % sulfur) is to be used, the double-alkali process (a solution scrubbing process as opposed to a slurry process) will give the least operating problems of the systems studied.

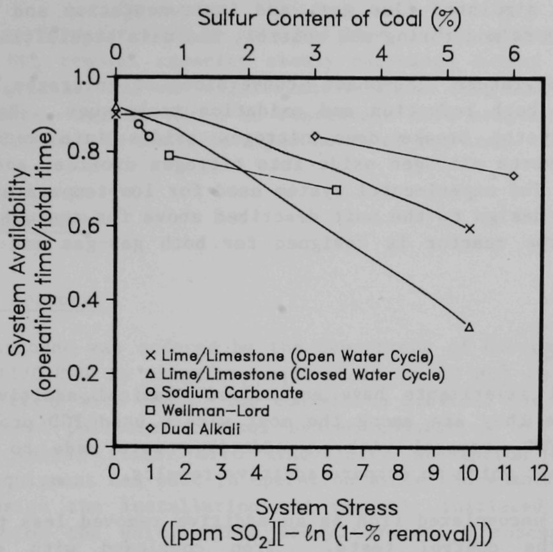


Fig. 4.2 Observed FGD System Availability for Five Scrubbing Chemistries

4.1.2 Combined Removal of Sulfur Oxides and Nitrogen Oxides

Scope and Approach

Two novel approaches to combined removal of sulfur oxides (SO_x) and nitrogen oxides (NO_x) from flue gas are being explored in EES laboratories. The first approach is to augment commercial SO_x wet-lime scrubber chemistry by incorporating chemical additives that remove NO_x. The second approach is to develop low-temperature gas-phase NO_x control systems that could be inserted after the air pre-heater of a boiler.

The approach being taken in the additive study is to evaluate systems that either can be retrofitted onto existing FGD systems or can easily be incorporated into a new system design. Five basic FGD process chemistries are now being studied: double alkali, Dowa, lime, Kobelco, and citrate. Since different process chemistries may require different additives for optimum operation, a screening program has been devised for evaluating each potential additive for all chemistries.

To evaluate this aqueous flue gas cleaning method, a bench-scale scrubber system is being used. This system consists of a gas-liquid reactor that can be operated in either batch or continuous mode; a gas delivery system to make up a simulated flue gas; and instrumentation and controls for gas analysis, process monitoring and control, and data acquisition.

Low-temperature gas-phase conversion of nitrogen oxides requires evaluation of both reduction and oxidation techniques. Reduction, with or without catalysts, breaks down nitrogen oxides into water and nitrogen. Oxidation converts nitrogen oxide into nitrogen dioxide, and subsequently to nitric acid. The experimental system used for low-temperature NO_x conversion is similar in design to the unit described above for aqueous NO_x/SO_x removal, except that the reactor is designed for both gas-gas and gas-solid interactions.

Results

Initial experiments have emphasized chemical additives for wet lime systems, since they are among the most widely used FGD processes. Control tests of SO_x/NO_x removal with no additives were made to develop a valid baseline against which to compare additive results.

Use of uncomplexed iron as an additive removed less than half the NO_x removed in the control tests. Iron complexed with ethylene diamine tetraacetic acid (EDTA) out-performed the control, but only for a brief period (Figure 4.3). Another complexing agent, nitrilo triacetic acid (NTA) showed marginally better performance than the control.

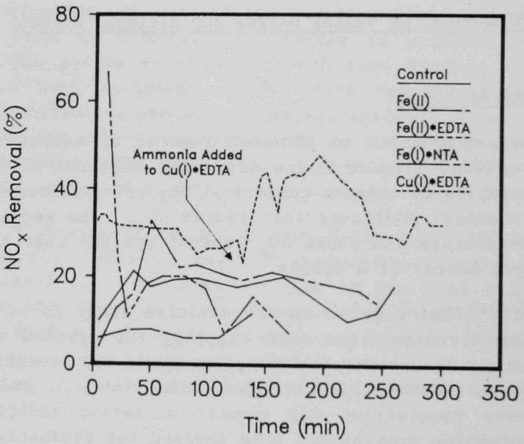


Fig. 4.3 Effect of Different Additives on NO_x Removal

The best performance seen to date has been with a copper-EDTA complex. This additive's NO_x removal capacity slowly decreased during the first two hours of the experiment, but was significantly better than the control at all times. Furthermore, ammonia added to reactivate this complex significantly enhanced its performance in the last three hours of the test.

4.1.3 Dry Scrubber Test

Scope and Approach

In 1979 Argonne was ordered by the Department of Energy to switch its largest boiler (170,000 lb steam/hr, equivalent to 23 MW) from firing with natural gas to firing with coal. The conversion provided the opportunity to install an advanced pollution control system consisting of a spray dryer absorber and a fabric filter with lime-slurry absorption of the sulfur dioxide. This equipment has been in operation since the summer of 1982. EES staff helped design the installation and recently initiated a performance monitoring study on the unit. This study involves a concentrated 90-day period of sampling and analysis, as well as a series of parametric tests of the system's operating characteristics.

The objective of the sampling and analysis is to evaluate the new flue gas cleaning system's performance with high sulfur (>4%) coal. These performance tests will generate baseline information for normal operating conditions. The objective of the parametric testing is to develop additional operating information, which will be used to develop a simulation model of system performance and operation. Such a model is required by designers and users of dry scrubbers for predicting performance over the full range of expected operating conditions. Testing of coals other than the standard coals normally burned will expand the applicability of this modal.

Results

Testing of sulfur oxides emissions demonstrated that the dry flue gas scrubber can meet the Illinois SO_2 emission limit of 1.2 lb per million Btu of heat input, even at a low load level (35% of maximum continuous rating). As shown in Figure 4.4, sulfur dioxide removal ranged from 80% to 95%, which meets or exceeds the 80% level of removal required by the Illinois Environmental Protection Agency.

Particulates removal by the fabric filter also has been very satisfactory, especially when compared to the Illinois standard of 0.1 lb/10^6 Btu. Since this is the first commercial application of this type of system with high-sulfur coal, these test results were considered to be significant.

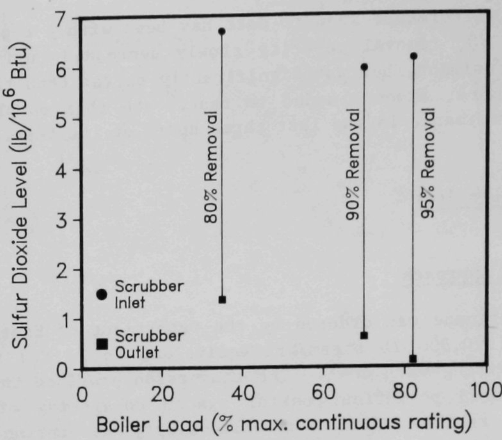


Fig. 4.4 Sulfur Dioxide Emission Levels during Performance Testing of Dry Scrubber at Argonne Boiler House

Another important result of the preliminary tests concerned the rate of removal of sulfur oxides as a function of system stoichiometries (calcium to sulfur molar ratios). Since this relationship affects system operating costs, a great deal of debate has centered on whether a dry FGD system could operate at the same stoichiometries, on high sulfur coal, as a conventional wet system. The data from the tests indicate that this is, in fact, the case. In addition, the data confirmed that the variation of system pressure drop with load is in accord with established theory, and is 30-60% lower than for a conventional wet scrubber equipped with either an electrostatic precipitator or a fabric filter. These findings demonstrate that use of a dry scrubber system for high-sulfur coal lowers operating costs considerably, compared to use of a conventional wet scrubber system.

4.1.4 Future Direction of Flue Gas Cleaning Studies

Our laboratory and field experimental facilities for flue gas cleaning research are a unique resource that has already attracted industrial interest in EES experimental work. These efforts are addressing new applications of currently used systems as well as new methods of control.

4.2 COAL CLEANING

4.2.1 Cost-Effectiveness of Physical Coal Cleaning

Scope and Approach

The technical and economic feasibility of physical cleaning of high-sulfur coals to reduce sulfur dioxide emissions during combustion was examined in this study. In a conventional physical coal-cleaning process, the uncleaned coal is first ground and mixed with water. Gravity separation -- by means of centripetal force in a cyclone -- is used to separate the relatively heavy sulfur-containing minerals from the lighter-weight coal. The product is a stream of water-saturated coal, which is then dried using an expensive, energy-consuming dewatering process.

The coal currently burned at 25 midwestern power plants was characterized by reconciling utility reports to the Federal Energy Regulatory Commission (FERC) with data supplied by the coal industry. The significant variations that occur in coal washing properties on a county-by-county and a seam-by-seam basis were acquired from an extensive analysis of U.S. Bureau of Mines coal. We then assessed the volume of coal now being washed in the absence of regulatory incentives. Based on this information, we compared the performance and economics of coal washing and flue gas desulfurization.

Results

The study showed that about 33% of the coal used in the power plants surveyed had been subjected to at least coarse physical coal cleaning. The principal incentives for this cleaning were (1) the extensive use of automatic mining techniques for deep mines, which extract large quantities of rock with the coal and virtually mandate some form of physical coal cleaning, and (2) the improvements in boiler performance and reliability that result from use of a cleaned coal.

We determined that expanded voluntary use of physical coal cleaning may be constrained by:

- Wider cost/benefit variations for physical coal cleaning plants than for FGD systems,

- A less favorable tax status for physical coal cleaning plants than for flue gas desulfurization systems.

- Lack of an assured market for cleaned coal,

- Shifting state and federal postures on environmental regulations affecting coal cleaning,

- Economies of scale for small producers of cleaned coal, and

- Marginal profits for physical coal cleaning operations.

Atmospheric emissions of sulfur dioxide from coal combustion were reduced an average of 29% by coal cleaning facilities operating with 80% coal recovery by weight (which corresponds to 82% recovery of the heating value). Although the average reduction was 29%, sulfur dioxide emission reductions ranged from 0% to 50% (the latter only for one coal), demonstrating that coal cleaning alone can not achieve the 70-95% levels of sulfur dioxide reduction possible with flue gas desulfurization. In fact, the data showed that only one of the coal cleaning operations surveyed was able to reduce sulfur levels by 50%.

If the technically feasible sulfur reductions using coal cleaning were the design base, physical coal cleaning would not be more cost-effective than flue gas desulfurization for most of the power plants surveyed. Finally, a comparison of the Illinois, Indiana, and Ohio power plants surveyed showed no statistically significant variation among the states with respect to percentage sulfur reduction, physical coal cleaning costs, or flue gas desulfurization costs.

4.2.2 Magnetic Coal Cleaning

Scope and Approach

Conventional physical coal cleaning processes make use of differences in mass density between coals and mineral impurities. However, it is difficult to physically clean fine-size coals. In a magnetic coal cleaning system, a finely ground stream of dry coal passes through a magnetic field, and the pyritic material is attracted by the magnet while the coal passes through. Because a dewatering step is not needed, magnetic coal cleaning offers an attractive alternative to conventional physical cleaning. Experimental tests have been carried out with small magnets at various research institutes and the results have been encouraging.

We have developed a test plan to use existing solids test facilities in Argonne's Applied Physics Division and a superconducting magnet (originally developed for physics experiments at Fermilab) to carry out a series of cleaning experiments on various types and sizes of coal under various sets of operating conditions (see Figure 4.5). A mathematical model is being developed to describe the separation process and predict system performance. The tests will identify important design parameters and validate the theoretical model.

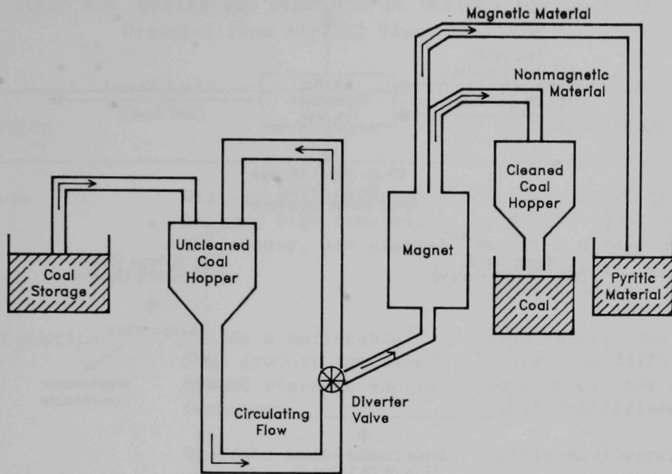


Fig. 4.5 Schematic Flow Diagram for Magnetic Coal Separation

Results

Although this is a new activity and no experimental results are yet available, a simple model has been built to predict magnetic separation performance. The computed results indicate that the test data to be obtained from the prototypical Argonne coal-cleaning equipment can be used for scale-up to commercial-size units.

Future Directions

In future efforts, we will develop an understanding of the phenomena of the magnetic separation process and evaluate applications of magnetic coal cleaning to coal conversion (to produce solid or liquid fuel or coal slurry).

4.3 ENVIRONMENTAL CONTROL FOR FERMENTATION ALCOHOL PLANTS

Scope and Approach

Production of fuel alcohol by fermentation has increased several-fold in the last five years. The impacts of fermentation alcohol production on the environment must be identified and quantified to guide the implementation of any necessary corrective actions. Figure 4.6 is a flow diagram of a typical fermentation alcohol production process.

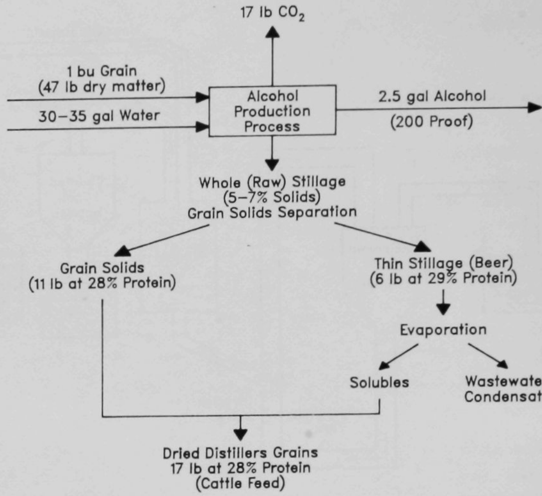


Fig. 4.6 Ideal Alcohol Material Balance without Direct Recycle and Reuse

Over the past three years, EES has worked closely with Argonne's Biological and Medical Research Division and with industry and university experts to formulate a balanced research and development plan for examining the environmental impacts of fermentation alcohol production. The existing literature was reviewed to establish what is known and to identify information deficiencies that are serious enough to warrant further investigation.

Results

The initial literature review revealed that the principal environmental concern in the operation of fermentation alcohol plants is the large quantity of waste organic material remaining in the wastewater produced from the evaporation of the thin stillage. Although grain solids can be filtered off and sold as animal feed, large amounts of organic material remain suspended or dissolved in the wastewater. Organic recovery by wastewater evaporation is energy-intensive and wasteful of water in dry regions, but there are better alternatives. Carbon dioxide is another major by-product that can be recovered and can be used in enhanced oil recovery, hydroponic gardens, and other applications.

The attributes of the three most promising technologies for wastewater organics removal are compared in Table 4.4. Although bio-oxidation is well established, it does not allow recovery of marketable by-products. The

Table 4.4 Merits and Drawbacks of Options for Removing Organics from Alcohol Plant Stillage

Option	Advantages	Disadvantages
Bio-oxidation	Well-established technology, high removal efficiency, low capital cost	No marketable by-products recovered, creates sludge requiring disposal, high utility costs
Anaerobic digestion	Yields a marketable fuel product (methane), 65% of organics energy recovered	High capital costs, process is difficult to control, low conversion efficiency
Acidogenic fermentation/ extraction	Yields a valuable chemical product (acetic acid), high conversion efficiency, process may be more controllable	Little development work done, extraction may be energy-intensive, system may be capital-intensive

alternative methods are less developed but offer means to recover additional marketable products from the wastewater.

Alcohol can also be produced from glucose provided by cellulose hydrolysis. Facilities using lignocellulosic feedstocks, such as wood or crop residues, must find markets for the other plant components (pentose sugars, acetic acid, methanol, and lignin). Sufficient revenues must be attained for these by-products for a lignocellulose-based alcohol plant to be economically feasible. We are currently developing methods such as supercritical fluid CO_2 extraction for efficient recovery of lignocellulose by-products.

Future Directions

We are completing preparations for a wastewater treatment laboratory to examine possible biological and physico-chemical treatments and by-product recovery options. Experiments are planned to determine the respective capital and operating costs and the by-product revenues that can be obtained using candidate control technologies. Experimental results will be used in a cost-minimization model developed by ANL researchers to determine the least-cost approach to removing organic waste from stillage.

By-product revenues can significantly improve the economics of fermentation alcohol production. EES research results will offer producers alternatives for complying with environmental regulations while enhancing production economics.

Longer-range plans include development of methods for (1) testing fermentation plant feedstocks and process streams for herbicides and pesticides and (2) detecting fugitive solvent emissions from distillation

5 RESOURCE CONSERVATION AND RECOVERY

The resource conservation and recovery program comprises four closely related investigations designed to develop economically viable processes for recovering useful energy by-products from what would otherwise be industrial waste products. In addition to improving the economics of the associated industrial operation, such resource recovery processes can reduce the adverse environmental impacts that would accompany the uncontrolled discharge of these waste products.

Current studies focus on technologies for (1) converting municipal solid waste to liquid fuels and methane, (2) producing ethanol from wood waste and other cellulosic materials, (3) using waste process heat for cogeneration, and (4) converting organics in industrial wastewaters into marketable fuels and chemicals.

5.1 ENERGY FROM MUNICIPAL WASTE

Scope and Approach

As lead laboratory in the DOE energy from municipal waste (EMW) program, Argonne is conducting research to create a generic data base on technologies that convert municipal solid waste (MSW) to liquid and gaseous fuels. The program is designed to develop methods for (1) producing high-quality liquid fuels and chemical feedstocks from municipal waste; (2) enhancing methane production from MSW, wastewater, and landfills; (3) energy-efficient dewatering of MSW and wastewater; and (4) producing, at low cost, high-mechanical-strength densified refuse-derived-fuel that is suitable for long-term storage.

Our work to date has concentrated on:

- Proving the technical feasibility of converting cellulosic materials to liquid fuels and chemical feedstocks,
- Developing a data base on volatile organic compounds and volatile mercury and other elements in raw and processed methane recovered from landfills,

- Identifying major causes of, and seeking solutions to, failures of refuse-derived fuel facilities, and

- Assessing the practicality of external combustor systems for refuse-derived fuel.

Results

Cellulosic material in municipal solid waste can be converted to organic acids through microbial degradation; the acids then can be used to produce liquid fuels and chemical feedstocks. We have conducted laboratory research into the production of fuels from short-chain organic acids. Our work has proven the technical feasibility of physico-chemical oxidation of aliphatic acids to alkanes, and high yields have been achieved. For example, we achieved up to 75% of the theoretical yield for the production of decane from hexanoic acid.

A program jointly funded and carried out by Argonne and the Gas Research Institute developed standardized sampling and analytical procedures for landfill gas, produced a data base on the amounts of volatile organic compounds (VOC) and volatile mercury in raw and processed landfill gas, and determined whether human pathogenic viruses and bacteria are present in the gas. The data, accumulated through a field measurement program and in-house chemical analysis, show a reduction in VOC concentrations from inlet (i.e., raw landfill gas) to product (i.e., processed landfill gas) to surface gas. (See Figure 5.1.) We found that mercury concentrations in the gas were 3 to 5

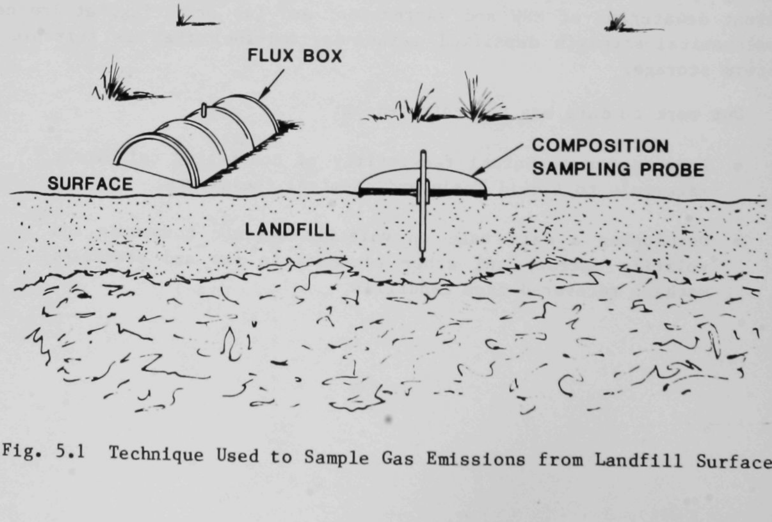


Fig. 5.1 Technique Used to Sample Gas Emissions from Landfill Surface

orders of magnitude below the health-effects threshold for inorganic mercury. No bacteria or human enteric viruses were recovered in any of the samples of inlet and outlet landfill gas, nor were pathogenic microorganisms detected.

Successful cofiring of refuse-derived fuel (RDF) with coal could reduce utility coal consumption by more than 10%, reducing sulfur emissions by the same amount. Our field review and evaluation of nine operating systems for feeding RDF to electric utility boilers show that the systems produce end products that can be burned successfully in conservatively designed boilers with dump grates installed to collect burning RDF (which burns 10-100 times longer than does pulverized coal). The major problems in the use of RDF are identified with refuse-derived fuel feed systems, clinker grinders, draft fans, and gas cleanup systems. Based on our analysis of this information, guidelines will be prepared for the preparation of RDF for cofiring with coal.

To date, the principal use of RDF has been as a supplemental fuel that is cofired with coal in a utility boiler. Our external combustor studies have examined an entirely different approach, i.e., to combust the fossil fuel and RDF separately and then combine the energy (Figure 5.2). In this way, both combustors can be designed to extract optimal heat from the respective fuel. Our initial analysis of a conceptual design for an external combustor indicates that while the boiler efficiency of an external combustor is 10-20% less than that of an RDF-cofired system, using the external combustor in conjunction with a coal- or oil-fired boiler may alleviate the operating problems associated with RDF cofiring. More detailed system analysis using computer simulation codes is planned.

Future Directions

Future research will address the basic parameters, kinetics, and heat transfer involved in the pyrolysis of municipal solid waste to product liquid fuels. Basic laboratory research into anaerobic digestion will be undertaken to further our understanding of the mechanisms by which methane is generated. Other laboratory research will focus on the production of short-chain organic acids and other valuable chemicals from the bioconversion of municipal solid waste. Field studies will characterize the composition of major gases drawn into a landfill and emitted from a landfill surface during methane recovery.

We will develop a systems model for evaluating and optimizing various unit operations for the production of RDF. In addition, fuel densification processes will be evaluated for their ability to produce a RDF that is easily transportable and suitable for long-term storage.

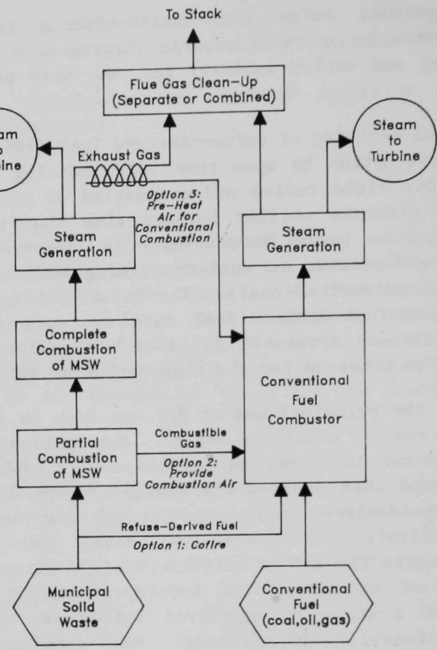


Fig. 5.2 Integrated System for RDF and Coal Combustion

5.2 ETHANOL FROM CELLULOSIC FEEDSTOCKS

Scope and Approach

Fusarium, a fungal genus including several species, has a unique ability both to break down cellulosic plant material into glucose and xylose and to yield ethanol through fermentation of these sugars. We are selecting *Fusarium* strains that hyperproduce ethanol, suitable for fuel use, from biomass feedstock.

After conducting an exhaustive literature review that revealed there was little experimental data on the ability of various *Fusarium* strains to produce ethanol, we developed a research program to (1) isolate, select, and develop *Fusarium* strains that show superior cellulolytic ability; (2) optimize the strains' ability to convert biomass to sugars and ferment the sugars to produce ethanol; (3) identify the enzymes involved and determine their characteristics; and (4) immobilize *Fusarium* cells in a bioreactor for the continuous fermentation of glucose and xylose.

Results

More than 3,500 *Fusarium* samples were obtained by isolating them from sources such as soil, plant debris, roots, and partially delignified wood. The *Fusaria* tested all indicated an ability to hydrolyze cellulose, and the best strains were selected for subsequent laboratory study. With respect to the ability of *Fusaria* to convert cellulose to glucose, most of the wild strains produced an average of 0.10 IU/mL (micromoles of glucose per minute/milliliter of the medium) cellulase, while selected isolates of *Fusarium* yielded an average 0.35 IU/mL and ultraviolet mutants of *Fusarium* yielded an average 1.00 IU/mL, or 10 times the yield of wild strains. These observations indicate that the ability of *Fusaria* to produce glucose from cellulose can be improved significantly through genetic manipulation.

When screened for their ability to ferment glucose to ethanol, several of the *Fusarium* isolates and mutants exhibited a conversion efficiency close to that achieved by yeast. Fermentations of 1% glucose with isolates from *Fusarium* strain ANL 99A-780 repeatedly generated ethanol at an efficiency close to 83% of the theoretical maximum. The significance of this is that *Fusarium* can ferment glucose almost as well as yeast can, in addition to its ability to convert cellulose to glucose. Brewing yeast cannot break down cellulose, hemicelluloses, and lignin, and cannot ferment pentose sugars as *Fusarium* can. *Fusarium* can thus operate on more constituents of biomass feedstock than can yeast.

Another main interest of our studies is the fermentation of xylose (a pentose sugar) to ethanol, since xylose is the main monosaccharide in plant hemicellulosic material and since it is not fermented by yeast and most other glucose fermenters. In consecutive fermentations of 1% solutions of xylose, selected *Fusarium* isolates and mutants produced up to 4.2 mg/mL ethanol within 48 hours, a yield higher than any reported for other xylose-fermenting microorganisms. Fermentation of higher xylose concentrations was tested with some isolates and mutants, and isolates from *Fusarium* strain ANL 22-760 produced more than 8 mg/mL ethanol in 48 hours from 2% xylose solutions.

The ethanol tolerance of the most efficient ethanol-producing strains of *Fusarium* also was tested, because ethanol is an antimicrobial agent that interferes with the growth and activities of *Fusaria*. All of the isolates could grow and produce ethanol in ethanol concentrations of up to 5%. This is an important capability for commercial applications of the fermentation technique.

Future Directions

It is anticipated that additional EES research will select *Fusarium* strains that show lignolytic (lignin-breaking) activity, identify *Fusarium* strains that produce cellulolytic enzymes (to break down cellulose to glucose), select *Fusarium* strains that tolerate higher ethanol concentrations, and develop new *Fusarium* strains through mutation and other genetic methods. Further studies also are planned on semiaerobic glucose and xylose fermentation by *Fusaria* and the immobilization of *Fusarium* cells for continuous fermentations.

5.3 INDUSTRIAL COGENERATION

Approach and Scope

The industrial cogeneration program analyzes the heat and power needs of energy-intensive industrial sectors to determine if advanced cogeneration technologies can meet those needs. The goals of our research are to evaluate the economics of alternative cogeneration systems, test the performance of system components, and help DOE monitor proof-of-concept demonstration units.

In one economic analysis, we determined the return on investment for 600-kW, 1200-kW, and 2400-kW Rankine power systems using six organic working fluids. For each organic fluid and each of several waste stream temperatures, a minimum-cost Rankine cycle system was designed. With specific assumptions about such factors as electricity costs, capacity factors, and operating and maintenance costs, we then calculated a return on investment.

In experimental work, we are evaluating the performance of various organic working fluids. To test the working fluids, we built experimental loops designed to replicate the working conditions of the Rankine-cycle systems in which they would be used. Fluorinol 85® is now being evaluated in a test loop, with the objective of characterizing the thermal degradation of the working fluid and the deleterious effects of contact with system materials. A dynamic 2000-hr test will be performed.

Additional test loops are to be constructed for 2-methyl pyridine, Freon R-113®, and toluene, and testing will conclude in about 18 months. The results of these tests will provide a data base for the design of systems optimally matched with industrial waste heat sources for greater efficiency, economy, and reliability.

Results

At working temperatures below about 700°F, steam systems in a Rankine cycle become costly and inefficient, but systems using other working fluids, such as organic compounds, can be economically attractive. The organic Rankine-cycle working fluid study showed that at current and projected energy costs, systems using any of the fluids studied can exceed the minimum return-on-investment criteria of most industries. Figure 5.3 shows these results.

Additional results from the program are related to proof-of-concept demonstration projects that were completed recently; Argonne provided technical management support to DOE for these projects. One project is the largest stationary low-speed diesel engine in the U.S. It was built to serve all of the electrical and some of the thermal needs of a major pharmaceutical plant. Our calculations indicate that this "first of a kind" plant is achieving a 26.4% effective annual after-tax discounted return on investment, with a simple pretax payback of 4.8 years. One concern with this technology is nitrogen oxides (NO_x) emissions. Our early data analysis indicates that at operating loads greater than 78%, NO_x emissions fall safely within the New Source Performance Standards for this size unit.

Future Directions

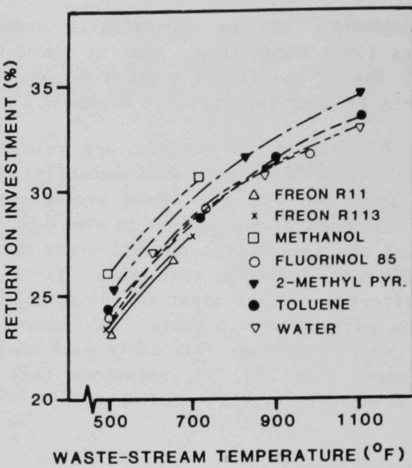
The future activities of the program will focus on the development of new experimental programs. One new experimental program that is just beginning will test the performance of advanced heat exchangers that could be used in Rankine-cycle systems.

A recently designed spirally fluted heat exchanger tube for condenser use has displayed desirable economic and thermal characteristics that make it a candidate for inclusion in future organic Rankine-cycle systems. A test program is now beginning that will evaluate the design, developed by General Atomic Corporation, using the existing heat exchanger test facility built originally for the OTEC work (described in Section 2 of this report). Other new tube designs may be tested later in the heat exchanger test facility, which offers many opportunities for cost-effective experimental work.

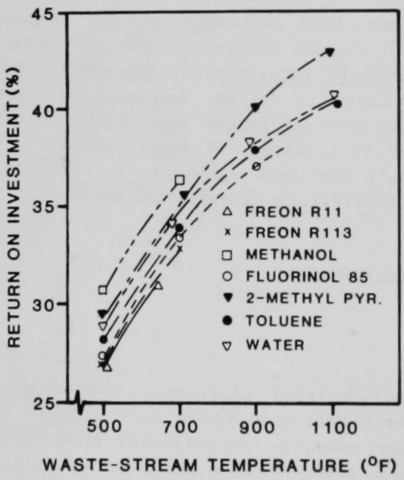
5.4 RESOURCE RECOVERY FROM INDUSTRIAL WASTEWATERS

Scope and Approach

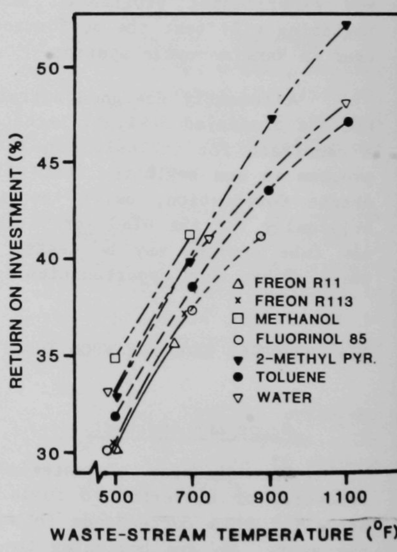
The quantity of materials in industrial wastewater that could be recovered or converted to fuels has been estimated to be over 3×10^8 tons annually; this corresponds to an energy conservation potential of 0.83 quad per year. We are beginning to evaluate methods for achieving this recovery through (1) biological and thermal conversion of organics in industrial wastewater to fuels and chemicals and (2) physical/chemical separations for recovery of acids, solvents, and metals. Our approach will be to develop new technologies to meet the wastewater treatment needs of industry through cost-shared projects with industry, government agencies, and universities.



a. 600-kW Power System



b. 1200-kW Power System



c. 2400-kW Power System

Fig. 5.3 Effect on Return on Investment of Waste-Stream Temperature in Rankine-Cycle Power Systems

Two research projects in anaerobic microbiology have recently been initiated. One is an ANL laboratory study of the biochemical pathways for degradation by bacteria of polyaromatic hydrocarbons and halogenated aromatics in wastewater. The results will be crucial to broadening applications of high-rate anaerobic reactors for treating complex hazardous chemical wastes. In the second project, the University of Massachusetts is receiving support as an Argonne subcontractor for a project co-funded by the National Science Foundation and the State of Massachusetts to characterize the structure of anaerobic films in high-rate reactors and to develop procedures to separate and identify the three types of bacteria in these films.

Two pyrolysis projects are being developed for the treatment of hazardous metallic and oily sludges. In continuation of a basic research project funded by the National Association of Metal Finishers, Purdue University has an ANL subcontract to elucidate the metallurgical chemistry of mixed metals reduction/separation in chemically complex sludges. A cost-shared contract with Amoco R&D Center and Standard Oil of Indiana is being established to study the conversion of hazardous oily refinery sludges to energy and nonhazardous residues using advanced pyrolysis technology.

Future Directions

Beyond the current R&D efforts, a project to develop a technique for recovering metals and acids from stainless steel pickle liquors is being considered for support. This is considered a high-priority research need by the iron and steel industry. The International Nickel Company and the American Iron and Steel Institute are considering providing funding support and technical expertise for such a project.

6 EXPERIMENTAL SYSTEMS FOR HIGH-ENERGY PHYSICS

The EES Division has recently begun to develop several areas of mutual interest with Argonne's High Energy Physics (HEP) Division. Our objective is to provide the systems approach to the planning, construction, and operation of the large-scale experimental systems that are typical of HEP activities.

At this particular time, there is one new experimental program in which EES personnel are actively participating and two programs in early negotiation stages.

The new program with active EES involvement is a study of nucleon decay in the inactive Soudan underground iron ore mine in northern Minnesota. The two projects in the proposal stages are the (1) design and construction of a solid neon calorimeter for use in Fermilab's 15-ft bubble chamber and (2) modification and relocation of a high-resolution spectrometer from the Stanford Linear Accelerator to the Tristan Electron Accelerator in Japan.

In all three of these programs, a study of system tradeoffs is a common thread. Tradeoffs among several requirements are needed, particularly in the nucleon decay program, which requires an underground installation in a spent mine shaft. The rock stability and strength must be balanced against rock hardness and proximity to other shafts. The choice of the structural support for the 5000-ton detector (hanging or standing) involves considerations of costs, safety, and accessibility. The mine, the first iron ore mine in Minnesota and a National Historic Monument, is toured each summer by 30,000 visitors. Obviously the project activities must be compatible with the present use of the mine.

We are contributing to the nucleon decay project by:

- Defining the technical requirements for the underground test site engineering,

- Conducting preliminary evaluations of the cultural resource and environmental implications of the detector installation in the mine, and

- Complementing the HEP engineering staff in the areas of detector development and structural engineering.

The initial feedback from the HEP Division regarding our participation in its programs is favorable, and there is reason to believe that a more active, broader participation by EES may develop in support of high-energy physics programs.

7 SYSTEMS ANALYSIS AND MODELING

This new programmatic area for SET includes modeling investigations of several engineering problems that stem from the Laboratory's work on magnetohydrodynamic (MHD) systems, pulse combustion burners, flue gas cleaning, and coal-water slurry combustion.

The fundamental heat and mass transfer processes and chemical reactions that take place within the components of these systems are analyzed mathematically in these studies. The systems are modeled by application of the appropriate equations describing the essential fluid mechanical and transport processes, and these equations are solved to produce information about system performance and its dependence on system operating conditions. Such information helps experimenters interpret laboratory and pilot plant results and helps designers predict system performance and costs.

By nature such systems analysis and modeling activities are an integral part of hardware engineering development work conducted throughout Argonne. For this reason, the Associate Laboratory Director for Energy and Environmental Technology established a core group to serve as a focal point for all Argonne systems engineering modeling for fossil energy, conservation, renewable energy, and other nonnuclear energy technologies. The EES Division was selected for this responsibility because modeling with a broad systems approach has been an important component of the Division's work for many years, as evidenced by the SET Group's highly successful investigations of pulse combustion furnaces, spray combustion burners, and compressed-air energy storage systems.

The following pages describe our current and recently completed systems analysis and modeling programs, beginning with a description of the MHD work carried out by staff members who recently transferred to the EES Division and concluding with brief summaries of EES investigations of pulse combustion furnaces and spray combustion burners.

7.1 FOSSIL ENERGY SYSTEMS

Scope and Approach

Most of the initial systems modeling effort by the personnel who recently joined EES supported Argonne's magnetohydrodynamics (MHD) program. Because MHD is a complex energy conversion system, there was a need for modeling and systems analysis to:

- Evaluate the complicated processes that occur in an MHD power plant,

- Clarify the system integration problems,
- Help design and evaluate MHD power plants,
- Evaluate experimental data, and
- Predict full-scale plant performance.

A system diagram of a proposed MHD power plant for coal combustion is depicted in Figure 7.1. The processes occurring in an MHD plant are much different than those in a conventional coal-fired power plant. Coal is burned under fuel-rich conditions in a pressurized combustor. The combustion gases are then seeded with an ionizing compound, and the resulting plasma is passed through an MHD generator at high velocities, where enthalpy is extracted and converted directly into electrical energy. The ionizing compound, besides increasing the electrical conductivity of the combustion gases, also combines with the sulfur dioxide in the combustion gases and eliminates that pollutant from the flue gases.

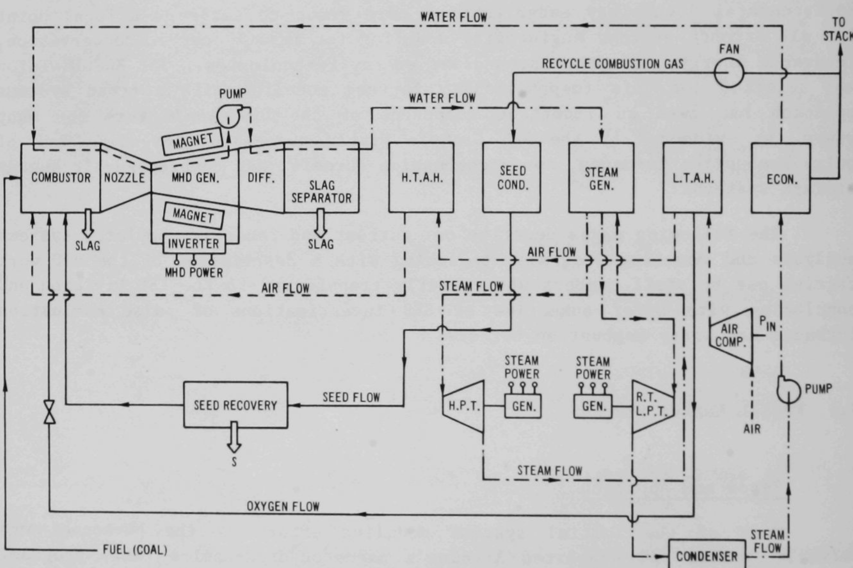


Fig. 7.1 Schematic of MHD Power Plant (H.T.A.H. and L.T.A.H. = high- and low-temperature air heater, H.P.T. and L.P.T. = high- and low-pressure turbine)

Results

Numerous computer codes were written to model MHD processes, such as nitrogen oxides (NO_x) kinetics; particle formation, growth, and deposition; chemical combustion; and chemical equilibrium. In addition, six major component models were developed using the process models as subelements. The components modeled were a combustor, MHD channel and diffuser, slagging radiant boiler, secondary combustor, generalized tube bank heat exchanger, and refractory-lined air heater.

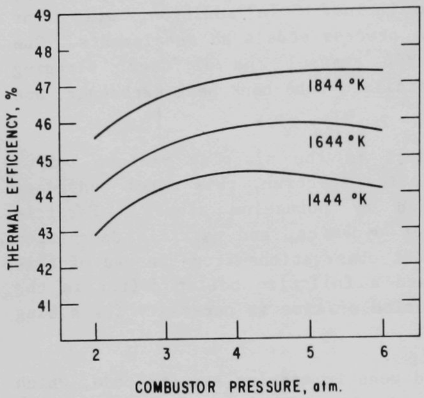
The most elaborate of these models is the slagging radiant boiler model. By evaluating the complete radiation spectrum, this model considers gas-particle radiation that is enhanced by potassium atoms. Particle deposition, NO_x decomposition, slag layer dynamics, and particle deposition are also included in the model. Important observations from the use of this model are that an experimental boiler and a full-size boiler differ in the mode of heat transfer and that a long period of time is necessary for a slag layer to build up.

Also developed was a sophisticated generic modular systems code, which has been applied to numerous technologies besides MHD. The Systems Analysis Language Translator (SALT) code contains state-of-the-art numerics to solve a system of nonlinear equations, perform optimizations, and perform integration. It includes cost computation routines as well as an extensive library of component models that can be linked to analyze different technology configurations.

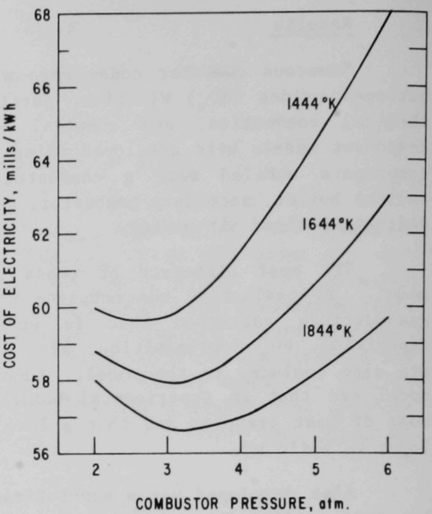
The SALT code has been used for design analysis; off-design studies; optimization, sensitivity, and retrofit studies; and dynamic simulation. It has been used to evaluate several types of MHD systems, fuel cells, advanced fossil-fuel power plants, OTEC plants, and nuclear power plants. With this code, we predicted that the optimal MHD plant parameters for maximum efficiency or minimal cost of electricity were much different. These differences are shown in Figure 7.2.

Future Directions

The MHD models will continue to be used as a basis for system modeling and analysis efforts. Our plans for further modeling focus on turbine blade fouling by gas streams produced by the burning of a coal-water mixture, burning municipal solid waste in conjunction with a fossil fuel-fired boiler, and particle agglomeration in a magnetic coal-separation system.



a. Thermal Efficiency



b. Cost of Electricity

Fig. 7.2 Variation of MHD Power Plant Efficiency and Cost of Electricity with Combustor Pressure (combustor input power = 2000 MW, steam cycle efficiency = 40%)

7.2 PULSE COMBUSTION FURNACES

Scope and Approach

The need to conserve fossil fuels in recent years has accelerated the development of more-efficient combustion systems for space heating. One such system is a pulse combustion burner, which consists of a combustion chamber connected to an open-ended tailpipe.

An initial charge of air and fuel is admitted to the closed end of the combustion chamber and is ignited (see Figure 7.3). As the fuel burns, the combustion chamber pressure rises, causing the valves that admit the air and fuel to shut and forcing the combustion products out of the tailpipe. The inertia of the exiting gases puts a partial vacuum on the combustion chamber, causing the inlet valves to open and admit a fresh charge of air and fuel. Since the combustion chamber pressure is less than atmospheric, some of the exhaust gases are drawn back into the chamber. The hot gases mix with the fresh charge of fuel and air, and this mixing self-ignites the fuel to complete the cycle.

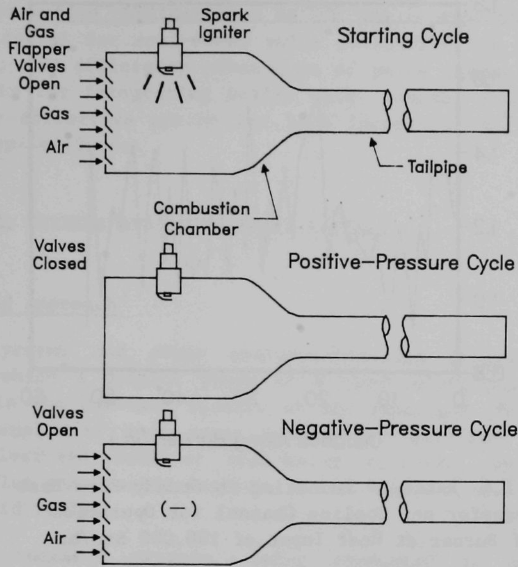


Fig. 7.3 The Pulse Combustion Process

Recently, several manufacturers introduced gas-fired pulse combustion water heaters and furnaces for the residential market. While fuel savings of 35-50% compared to conventional heating systems have been demonstrated, the development of pulse combustion systems has been hindered by their inherently high noise levels and the complexity of their operation.

Current designs have evolved by trial and error, with the result that little generic knowledge is available on the performance of pulse combustion furnaces. To address this information deficiency, a combined analytical and experimental program was conducted by EES between 1978 and 1981. The program developed design data and procedures for predicting fuel utilization efficiency, noise levels, heat transfer efficiency, and operational stability and reliability. A test program was conducted with a water-cooled gas-fired pulse combustion burner designed and built by EES. The nominal heat input rate for the burner was 150,000 Btu/hr, typical of residential furnaces.

Results

Figure 7.4 shows the results obtained for burner heat transfer behavior; the oscillatory pattern of the heat transfer rate along the burner wall is clearly evident. We found that the heat transfer was 25-40% greater

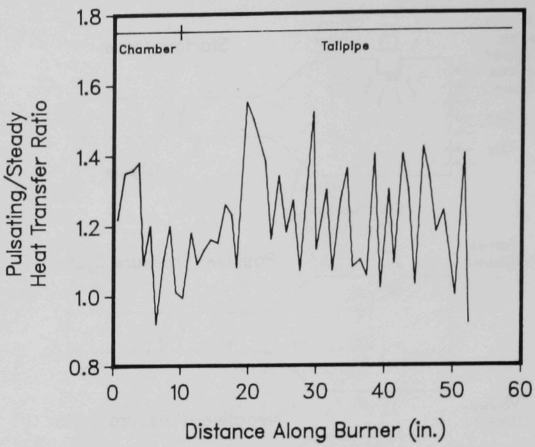


Fig. 7.4 Ratio of Pulsating to Steady-Flow Heat Transfer per Cooling Channel for Operation of Burner at Heat Input of 100,000 Btu/hr

than that obtained for conventional steady-state burners, due to the high-velocity oscillations and turbulent mixing achieved by the pulsating flow.

An analytical model of the pulse combustion burner was also developed to predict the pulsation frequency and peak pressures produced in pulse combustors. Comparison of the analytical and experimental results indicated that the predicted pulsation frequencies showed good agreement with observed values, and that the model could be applied to predict the burner pulsation frequency for other geometrical furnace configurations. Empirical relationships also were established for the noise output as a function of the fuel burning rate. It was determined that the noise levels were 25-30 decibals higher for the pulse burner than for an equivalent steady-flow burner.

Reliable operation was achieved for a range of heat inputs, air/fuel ratios, and geometrical configurations. We believe that our research established, for the first time, empirical relationships among heat transfer, emitted noise, heat inputs, and firing frequencies over a wide range of operating variables for pulse combustion furnaces.

Future Directions

Based on the accomplishments of the research on gas-fired pulse-combustion furnaces, we have proposed an investigation of the application of the pulse combustion concept to pulverized-coal-fired burners. This proposed project is under active consideration by DOE and is expected to be funded next year. The potential for coal-fired pulse combustion for industrial furnaces is significant; the efficiency advantages of pulse combustion, combined with new EES concepts for integrating sulfur oxide removal into the furnace unit, make it a very attractive option for both industrial heating and industrial cogeneration applications.

7.3 LIQUID-FUEL BURNERS AND OTHER SPRAY SYSTEMS

Scope and Approach

Power systems and other energy-conversion processes often include components in which a droplet phase or a particulate phase dispersed in a carrier fluid is the dominant feature of the important physical and chemical processes. Examples of such spray systems are oil-fired burners, furnaces fired with pulverized coal or coal-water slurries, spray dryers, spray scrubbers for flue gas desulfurization, diesel engines, and turbine combustors fired with liquid fuels.

An SET research program, being conducted in collaboration with researchers from the University of Illinois, is providing a theoretical basis for predicting system performance, interpreting experimental results, and establishing engineering guidelines for optimal system design. The emphasis is on improving spray system efficiency and enhancing pollutant emission control.

Two research efforts are underway. One is evaluating spray combustion processes with evaporation and exothermic reactions, and the other deals with spray dryers and scrubbers with evaporation and nonexothermic reactions. Both of these projects have been developed using a group-interaction analysis that accounts for the large-scale, collective interactions of droplet aggregates that form in spray systems. Theoretical models are being constructed and validated by comparison with experimental data from several different test facilities.

Results

A number of significant advances in spray combustion analysis have been accomplished by the SET modeling efforts. These include:

- Theoretical prediction of the principal combustion modes: external group combustion, internal group combustion, single droplet combustion, and external sheath combustion (see Figure 7.5);

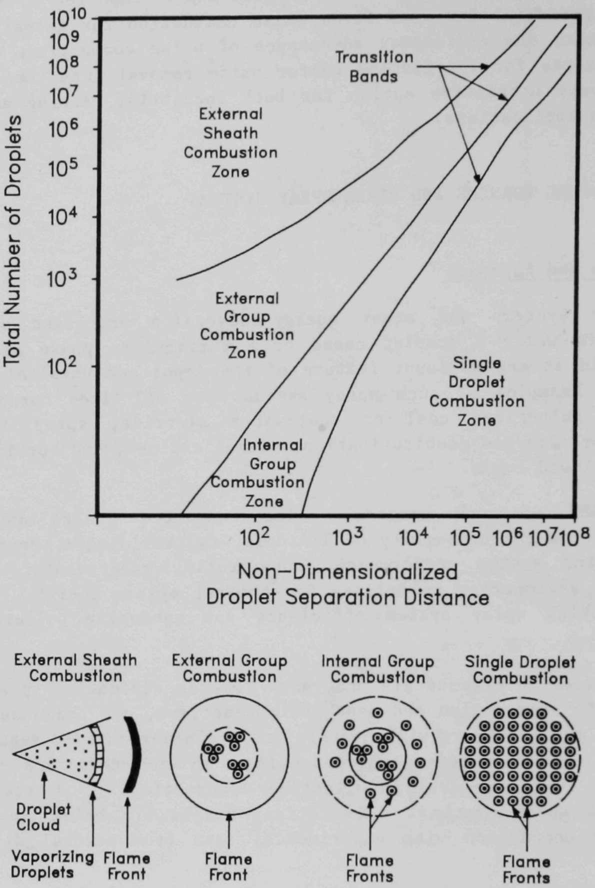


Fig. 7.5 Modes of Group Combustion

- Prediction of the operating range for the occurrence of these modes; and

- Explanation of spray structure and its impact on pollutant emissions.

Other modeling results have shed light on the complex spray combustion flame structure and the factors that control it.

In the second research area (i.e., sprays with evaporation and non-exothermic reactions), we are developing a physical model and a computer algorithm that will permit the prediction of spray scrubber desulfurization performance and that will provide an analytical basis for interpreting experimental data from the spray scrubber currently operating on the Argonne boiler (see Sec. 4.1).

Preliminary analysis has revealed that sprayer design has a significant impact on the cascading evaporation of aqueous alkaline droplets injected into the turbulent recirculating environment of a scrubber. Spray parameters and injection conditions that control the spatial distributions of droplets and the lifetime of droplets of various size are being evaluated to aid in sprayer design.

Future Research

The physical modeling of spray scrubbers will be completed and the results of the analytical and numerical simulation will be compared with experimental data. Spray group combustion studies will also be extended to evaluate the overall combustion efficiencies of industrial furnaces, diesel engines, and turbine combustors. Finally, a basic study concerning short-range droplet-droplet interaction and its effects on spray phenomena and system efficiency will be initiated to examine the characteristics of dense spray systems.

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X